DEVELOPMENT OF THE MORE INTENSE STORMS IN A WELL ORGANIZED SQUALL LINE

by

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ABSTRACT

The structure and behavior of the more intense storms in a well organized squall line were investigated in as much detail as permitted by the resolution of available radar data. Individual cells within the storms were tracked and statistics concerning number and duration of cells were presented. Similar analysis was made for 9 air mass thunderstorms that occurred on August 28, 1965 in order to see whether any differences in behavior exist between the two types of storms.

Raingauge data for the squall line were analyzed to see the areal extent of the line outside of the radar range. Records of available upper-level winds were examined for both days on which the squall line and the air mass storms occurred.

The results of the study indicated that in both cases most of the storms consisted of a sequence of relatively short-lived cells, each lasting about 20 minutes. Also in the two cases, the large majority of new cells developed close to the bottom right of decaying cells. While the cells within the squall line moved to the right of upper-level winds those of the air mass storms moved to the left of the winds. However, wind data from three stations only were used and these were quite inadequate for these results to be considered well established.

It was not possible, from this study to explain the existence of relatively large areas of less intense radar echoes usually found

between the more intense storms in squall lines, and thunderstorm complexes.

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Title: Research Associate

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I. INTRODUCTION

A good deal of attention has been given to the environmental conditions which encourage the development of thunderstorms and squall lines, so that occurrence of these phenomena can usually be predicted. Details concerning the precise configuration and locations of the storms are not so well understood, however, and there is considerable disagreement among meteorologists as to why storms have to form in well-defined lines. Many investigators (for example Tepper, 1950; Newton, 1950; Newton and Newton, 1959) have suggested theories that might explain the dynamics of squall lines. Most of their explanations, while assuming the presence of a convectively unstable air mass, focus attention on the triggering mechanism.

Since the application of radar to storm observations, several studies have been made of the behavior of the squall lines as a whole; the most extensive investigation being that of Byers and Braham (1949). Boucher and Wexler (1961) and Swisher (1959) have all studied the development and behavior pattern of New England squall lines. As an extension of these latter investigations the internal structure of squall lines was considered by Cochran (1961) who found that they contain relatively intense portions or "storms" spaced 25 to 30 miles apart on the average. These "storms" are evidently complexes rather than single convective cells, and it is the aim of the present investigation to study the internal structure of a squall line in somewhat finer detail than that provided by Cochran's analysis.

Considerable advances have been made towards the understanding of the dynamics of individual thunderstorms. In recent years several models have been proposed to explain the circulations within these thunderstorms. Ludlam (1963) has undertaken a review of a number of these models. The first of these models to be based on quantitative measurements resulted from a study by Byers and Braham (1949). In this model each thunderstorm cell has an evolution through three principal stages, namely (i) the cumulus stage, (ii) the mature stage and (iii) the dissipating stage. This basic model has been widely accepted by most workers. Browning and Ludlam (1960) and Newton (1960) have also constructed models in which the environmental wind field is given a prominent role. Further research still continues in this direction.

It would thus be apparent from the foregoing paragraphs that only the structure and behavior of the squall line or the larger entities (storm complexes) within them have been studied in detail. On the other hand, individual thunderstorms have been considered as separate entities rather than in the context in which they appear within the squall lines. Consequently there is a missing link, between these two scales of study, which must explain the behavior of the individual thunderstorms in relation to the squall lines. It is the purpose of this study to provide this missing link.

The investigation is based on quantitative radar observation of a well developed squall line. The appearance, duration and motion of small intense echoes within the line will be analyzed in as much detail as permitted by the resolution of the data. A few cases of isolated air mass thunderstorms will be studied in a similar manner to see if the cells within them exhibit the same behavior, as those within the squall line. Finally, the results of the analysis are discussed in the context of existing thunderstorm models.

The radar is the only meteorological tool capable of giving a quantitative description of such micro-scale features of the squall line. However, resolution in both space and intensity is still inadequate for an entirely satisfactory analysis to be made.

II. BACKGROUND AND STATEMENT OF PROBLEM

A. General Squall Line Development

One of the remarkable features of large-scale organized convection is the tendency for storms to occur in lines, which may consist of several clusters of storms. This is commonly called a squall line or an instability line. Squall lines with severe thunderstorms almost invariably form in warm tropical air masses particularly in the warm sector of developing extra-tropical cyclones in the lower middle latitudes. Since low-level convergence is associated with cyclone development it appears that such convergence in warm and moisture-ladden air is a favorable condition. Also presence of dry air aloft is a condition which precedes the development of a squall line. Petterssen (1956) has given more detailed description of the general features of squall line development.

Most squall lines in the United States develop in a region of warm advection at low levels, with neutral or even slight cold advection aloft. Through such differential advection a steep lapse rate is maintained through a deep layer, and as a result, convective currents are maintained over relatively long periods. Finally, the distribution, along the vertical, of moisture is important to squall-line development. This is in consequence of the condition of convective instability which has to be satisfied. Of equal importance is the horizontal distribution of moisture.

On the theoretical side, only relatively little is known about the dynamics of squall line, and the strong tendency of thunderstorms to form in well-defined lines has not been fully explained. One of the older theories is that a squall line is the result of a cold front aloft. A difficulty with this explanation is the frequent lack of any evidence of a front aloft prior to the formation of the squall line.

A theory that has enjoyed wide appeal is due to Tepper (1950). His hypothesis was that the squall line might be considered as a "pressure jump line", moving as a gravitational wave along the warm sector inversion. The jump is presumed to be initiated originally by a temporary acceleration of the cold front, precipitation being released by the lifting of air above the inversion as the wave moves along it. Although various objections have been raised to Tepper's theory, it does appear that such a mechanism often exists and is capable of releasing instability. An excellent example of a gravitational wave with marked surface pressure jump is contained in a study by Reed and Prantner (1961), though the convective activity associated with the pressure jump line was exceedingly slight. The pressure jump would thus appear to be a possible, though not sole trigger of squall lines.

Newton (1950), using data from the thunderstorm project, made a detailed three-dimensional analysis of a pre-frontal squall line. In this case the thunderstorms formed first over the cold front surface and subsequently moved into the warm sector. He therefore suggested that squall-line activity can be accounted for partly by the continuous generation of new thunderstorms. This will be a result of convergence-divergence pattern produced by the vertical transfer of horizontal momentum in pre-existent thunderstorm. This, according to Newton, is augmented by solenoidal circulations due to unbalance between the "thermal wind" and the actual vertical mixing of horizontal momentum. An essential source of energy for maintaining squall line activity appears to be the kinetic energy of air brought down from higher levels.

In a further study of the dynamics of squall lines Newton and Newton (1959) suggested that the physics of convective clouds depends not only upon thermodynamic processes but also upon the interactions with the environmental wind field. They put forward the hypothesis that when vertical shear is present a hydrodynamic pressure field is induced by relative motions near the boundaries of a large convective system which does not move with the ambient winds. This tends to make the clouds tilt away from the vertical, but at the same time vertical gradients of hydrodynamic pressure aid the formation of new convection. Also these authors derived expressions for the acceleration concerned and showed that they are of the same order as those associated with ordinary bouyancy forces. These account for the self-propagating nature of squall line type of thunderstorms and their ability to continue at night when thunderstorms in stagnant air masses tend to die out.

In summary, all the explanationsrequire the presence of a convectively unstable moist air mass, and attention is focussed on the triggering or lifting mechanism. In Tepper's theory a gravitational wave or pressure jump line, created by an acceleration of the cold front, is the activating mechanism. According to Newton, the cold frontal lifting initiates the line which then becomes self-propagating as a result of vertical exchange of momentum and moves out ahead of the front. Both of these possible lifting mechanisms appeared to be present in the case studied by Reed and Pranther (1961). In general, however, they are not evident with sufficient consistency for the nature of the triggering mechanism to be considered as clearly established.

B. Behavior of the Squall Line as a Whole

Considerable research has been carried out to identify the large-scale synoptic characteristics of squall lines. Byers and Braham (1949) studied extensively the behavior of squall lines. These authors found the following to be the most outstanding characteristics of squall lines: (i) Pre-frontal squall lines are parallel to the related cold front in most cases, though individual lines show variations in this respect. (ii) The speed of movements of the squall lines bears little or no relationship to the speed of associated front. This result is not in strict agreement with those of Harrison and Orendorf (1941), who found that, in the mean, the speed of movement of the front was less than that of the squall line. However, since the phenomena considered in the two studies are not strictly identical, discrepancies in the result are to be expected. (iii) Squall lines are frequently observed to last for periods as long as 24 hours during which they may travel hundreds of miles. (iv) The motions of the lines are significantly correlated with the 700 mb wind components, with the correlation smaller at higher or lower levels. (v) The lines are invariably oriented in a direction clockwise from the 700 mb wind direction.

Boucher and Wexler (1961) investigated the motion and duration of New England squall lines as an entity, based on normal PPI radar data. They found that most of these lines have some of the characteristics noted above. A particularly outstanding behavior of New England squall lines, according to these authors, is their preferred orientation, which is almost always from 30 to 210 degrees azimuth. Boucher and Wexler also noted that the speed of movement of New England storms range from 8 to 42 mph with a mean of 22 mph.

Swisher (1959) also studied the development and behavior pattern of New England squall lines by use of radar signal intensity contours and rainfall data of the U.S. Weather Bureau raingauge network. He found that squall lines moving into New England increased in intensity in the region from the Berkshire Mountains to the Connecticut River Valley. Regions of decrease were noted along the coast of Maine and the extreme southern coast line of New England. Swisher also found an average of three hours between the time when a line was first identified and when maximum intensity was reached.

C. Internal Structure of Squall Lines

Until quite recently attention has been focussed on the behavior of the squall line as a whole, and the distribution of precipitation within the squall line and the behavior of individual areas of heavy precipitation have received little consideration.

Cochran (1961) investigated the internal structure of New England squall lines through digitization of radar signal intensity contours.

His results showed that regions of more intense activity were spaced 25 to 30 miles apart along the line with lighter precipitation in between. These more intense activities usually lasted about an hour, and they moved to the right of the 700 mb winds more slowly. Cochran also observed two types of pre-cold frontal squall lines. The first type exhibited one single maximum in the time variation of the total rainfall intensity, which suggested that majority of the more intense cells occurred at the same time. The second type had several total rainfall intensity maxima along their lengths.

Austin (1962) has also observed in the squall lines studied by Cochran (1961) that three periods in the life of a squall line are identifiable from the time variation of the total rainfall intensity, namely: (i) the early period when the line is recognizable as a squall line; (ii) the period of peak intensity, taken as the time during which the total intensity is as much as 70% of the maximum recorded value and (iii) the period of weakening or dissipation.

D. Structure of Individual Thunderstorms

A number of investigators have been concerned with the internal circulation in a convective storm which is composed of a single cell - an updraft with its accompanying inflow, outflow, cloud, precipitation, downdraft etc. Generally, the thunderstorms associated with squall lines are little different from any others, except for a tendency to be more severe, especially in producing effects at the surface such as strong gusty winds. In view of this, it may be instructive to examine the structure of the thunderstorm by reviewing the various models that have been proposed. Hopefully, a knowledge such as this may be capable of explaining the organization of such individual thunderstorms into a well defined line.

Ludlam (1963) has undertaken a review of a number of thunderstorm models. The concepts that form the basis for most of these models are at best qualitative. However, a model based on quantitative measurements has been proposed by Byers and Braham (1949). In this model, a thunderstorm is typically a complex, built of several cells, each of which has an evolution through three principal stages: (i) Cumulus stage, in which updrafts are found everywhere in the cloud. Precipitation usually forms abruptly in mid-troposphere. (ii) Mature stage: with the beginning of rain at the ground a downdraft appears in the cloud. Throughout this stage the updraft persists and is perhaps found partly above the downdraft. Updrafts are warmer and downdrafts colder than the clear air environment at the same level. (iii) Dissipating stage: As the cold downdraft air spreads out below the cell, the updraft weakens and disappears and the downdraft will then extend to occupy the entire cell, but also weakens and eventually disappears.

Fig. 1 shows these three stages of development. The basic form of this model has been widely accepted, yet it is highly simplified and active storms are usually considerably more complex.

More recently a great deal of research has been geared towards models which will explain the interior anatomy of large, long-lived hailstorms that occur frequently in the middle latitudes. Browning and Ludlam (1960) used the detailed radar and ground observations of a particular hailstorm that occurred in England to refine a model of the airflow within a travelling storm. Their model is shown in fig. 2. Here the updraft is shown tilted at an angle of about 45 degrees to the horizontal with air entering in the low levels from the north-east. The tilted draft allows rain to fall from the updraft and not impede its upward motion, while at the same time the precipitation induces a downdraft. The model shows air entering the rear of the storm in the middle tropopause, descending in the downdraft, and leaving the storm as a northeasterly current near the surface. The circulation allows the updraft and downdraft to exist together in an organized manner, which allows the storm to maintain itself. Furthermore the intense updraft provides a mechanism which recirculates small hail stones until they reach a size which can no longer be supported by the draft.

Using data from the United States Weather Bureau hydro-climatic network of recording raingauges, Newton (1959) observed the movement of individual rainstorms over paths several hundreds of miles long during periods of up to 12 hours or more. The storm track was on the average directed at about 20 degrees to the right of the mean wind in the layer 850 to 500 mb. On the basis of this and previous work Newton (1960) constructed a new cumulonimbus model (fig. 3) in which, for the first time, wind shear was given an important role in intensifying and prolonging the convection, causing continual regeneration on the forward right flank.

E. Relation of Individual Storms to each other and to the Line as a Whole

Thunderstorms often develop as members of groups of storms that tend to become organized into identifiable families, which may be either in lines or scattered about. The individual storms have lifetimes on the order of a few minutes to one hour, while the line and the larger complexes last for a few hours (see Battan, 1959). Thus the individual storms which make the entire line are constantly changing - old ones dissipating and new ones developing along the line. This would suggest the existence of a preferred line formation.

The individual storms generally move in a direction which is clockwise from the axis of the squall line but never by as much as 90 degrees, a fact first observed by Byers and Braham (1948). In consequence of this, the echoes usually have a component of movement along the line and toward the left working along the direction of the squall line. Fig. 4 shows a schematic illustration of the movement of a squall line and the individual echoes in the line. In long squall lines, the individual storms on various parts of the line sometimes move at different velocities. The average differences in any time found by Byers and Braham (1949) were 12° and 6 miles per hour. This, the authors felt, resulted because the wind variations over a distance of several hundred miles sometimes were fairly large.

Observation shows that the motion of these individual storms is closely related to the prevailing upper level winds. Results from Byers and Braham's studies indicate that most storms move with prevailing wind and last less than an hour; while exceptionally intense storms last longer and move to the right of prevailing wind. Various explanations have been suggested for this behavior. Newton (1959) has attributed this to the fact that the storm cell is continuing to build up on one side and dissipating on the other. According to Fujita, Wilk and Franhauser (1966) this behavior of the storm motion is due to cyclonic rotation. Although rotation is not clearly substantiated by radar pictures, these authors have computed cyclonic and anticyclonic circulations near the earth's surface, associated with the storm echoes. They found that the sign of this local circulation is related to the eventual path taken by the storm echoes.

Another explanation for apparent motion to the right is that the storm consists of a series of separate cells each of which moves with the prevailing wind while new ones consistently form to the right of decaying ones. Byers and Braham noted a strong tendency for new cells to form in the vicinity of old ones and suggested the following reasons: (1) cold-front action of the outflowing cold air in underrunning and lifting the neighboring warmer air; (2) nourishment of new cloud development with saturated air entrained from the parent cell; (3) addition of moisture to the neighboring air by light precipitation falling from an overhanging cloud canopy which has grown out of the parent cell; (4) spontaneous production of updrafts in the area of cell clusters due in some cases to thermal or orographic processes, but in a homogeneous level region, apparently caused by local areas of surface convergence or upper level divergence.

Patrick (1960) has also studied the problem of preferred region of new cell development. He looked at the problem from the point of view of the effect of released latent heat in initiating new storms in a squall line. Basing his study on a two-dimensional steady-state model where a large number of stationary heat sources were evenly spaced in a line and imbedded in an atmosphere whose motion was uniform, he found that perturbations due only to the heat sources produced vertical velocities of sufficient magnitude to serve as a triggering mechanism for new storms. Furthermore he found that the preferred position for upward vertical velocities were quite close to the existing storms.

F. Statement of Problem

Studies described in previous sections are primarily concerned with the fairly large (on the order of 10 miles in horizontal dimension) storms or complexes within squall lines. The author decided to study the internal structure of these storms in as much detail as permitted by the resolution of the data, in an attempt to obtain more definitive information on such questions as (1) Are there preferred sections of the squall line for the development of intense storms? (2) Do intense storms of relatively long duration consist of a single more or less steady-state cell or of a sequence of cells of moderate life times? (3) How much information can we obtain regarding the motion, duration and variation in intensity of these intense cells? (4) How does the development pattern of these intense storms effect the apparent life times and motions of the larger entities? (5) Is there a preferred position with respect to existing cells for the development of new cells? (6) Do relatively large areas of less intense echo represent the area of influence (through environmental mixing or some other mechanism) of the intense updrafts within them? Or are they made up of other weaker cells not discerned? Or are they more stratiform in nature, that is, part of a general area of lifting in the vicinity of the front, while the strong cells represent points where the instability is released?

Analysis is based on a detailed case history of a selected squall line. Comparison is also made with air mass thunderstorm complexes.

III. DATA AND METHODS OF ANALYSIS

A. Selection of Squall Line and Air Mass Storm

A careful survey of film records for the years 1964 and 1965 was first undertaken. These records were preferred to those of earlier years because of improved instrumentation in the SCR 615-B radar. Eventually the film record showing two squall lines on August 19, 1965 was chosen. One of these squall lines had formed very early in the morning of August 19, and it was very close to the radar site. The other one formed in the afternoon on the north western edge of the radar range. This latter case was selected for detailed analysis. The primary factor responsible for the selection of the particular squall line was the continuous record of radar data available for most of its life time. Furthermore, radar records showed the squall line to be of average intensity and as having a high degree of organization.

On the same day the squall line appeared, a cold front moved into New England from the west. This cold front was oriented south-west to north-east. By afternoon it had moved quite close to the radar range; and at this time, the squall line was less than a hundred miles in advance of the front. The 500 mb flow was from south-southwest.

For purposes of comparison, nine isolated air mass thunderstorms that appeared on the radar at various times on August 28, 1965 were selected for detailed analysis. A low pressure center had situated west of New England on the previous day. By the afternoon of August 28, this low had advanced close to the radar range. Most stations in Massachusetts and east of the frontal system reported thunder and showery activities, flow aloft was southerly.

B. Radar Data

Data obtained from the SCR 615-B weather radar located at Massachusetts Institute of Technology and operated by the M.I.T. Weather Radar Research Project were used for this study. The SCR 615-B has a beam width of 3 degrees between half-power points and a wavelength of 10.7 centimeters. The elevation is usually set at one degree for plan position observation, so as to get most of the power above the horizon, which is close to 0.5 degrees at most azimuths. For the data used, the radar range was 120 statute miles. The radar data were in the form of maps of range-normalized signal intensity levels photographed on 35 mm film. The levels are at 5 db intervals and are photographed in sequences. Data from both Range-Height Indicator (RHI) and Plan-Position Indicator (PPI) were available from the SCR 615-B radar. But most of the data used were from the PPI – the RHI serving only to show the vertical structure of a few of the cells.

In order to obtain quantitative information from the radar data, use has to be made of the Rayleigh formula. This is an approximation of the Mie equation (see Battan, 1959) and it gives the reflectivity η per unit volume as

$$\eta = \frac{\pi^5 |K|^2 Z}{\lambda^4} \qquad (1)$$

where $Z = \Sigma D_i^6$, the reflectivity factor

D_i = diameter of individual particles

λ = wavelength of the radar

$K = \varepsilon-1 / \varepsilon+2$

where ε is the square of the refractive index. For water, $|K|^2 = 0.93$ and for ice, $|K|^2 = 0.197$. When Z is obtained from measured radar reflectivity rather than from direct observation of the hydrometeors, it is called equivalent Z, denoted by Z_e. Rayleigh approximation holds fairly accurately for particles with diameters less than or equal to 0.06 of the wavelength. From the radar calibration of the particular day under study, Z_e can then be computed for each intensity level. Using the empirical relation

$$Z = 200R^{1.6} \tag{2}$$

the rainfall rate R in mm/hour can then be obtained. The interval between intensity levels, which is some 5 db corresponds to a factor of two in equivalent rainfall rate. Table 1 shows each intensity level and the corresponding log Z_e and rainfall rates.

The accuracy of the radar measurements of η have been estimated by Austin and Geotis (1960) to be about 2 db for the SCR 615-B radar. Since even large raindrops are well within the Rayleigh scattering region, the values of Z_e are equally accurate. Another important factor in the radar data that might seriously impair the accuracy of this study is the radar resolution. The resolution of a radar system is limited chiefly by the angular width of the beam and the pulse length.

Bent, Austin and Stone (1950) have discussed how these factors affect the radar display. The finite length of the radar pulse may cause distortions in the radial dimensions of the echoes (but these are always less than 250 meters) and determine the limits of the resolution of range measurements. There is also a distortion which results from a finite beam width. The SCR 615-B radar has a beam width of 3 degrees which is larger than the 1 degree radar. At great ranges, the volume sampled by the radar is so large that distortion results.

C. Raingauge Data

Hourly precipitation reports from the network of raingauges throughout New England and New York State were used to determine the extent of the squall line outside of the radar range. An attempt was also made to determine from them whether the line was actually forming at the start of the radar observation. However, the wide spacing of these raingauges and consequent lack of definition of the line at any one time placed a limitation on the amount of information that could be gained from such an analysis.

D. Upper Level Wind Data

In order to obtain a knowledge of the wind field on the two days of interest to this study, upper air soundings available for 0700 and 1900 EST were recorded for the three stations, Portland, Albany and Nantucket. In view of the geographical locations of these stations the upper level winds over Albany at 0700 EST on August 19, 1965 were taken to be representative of the environmental wind field during the early period of the squall line, while those of Portland and Nantucket at 1900 EST were assumed to represent the general situation aloft during the latter period of the squall line. In addition to these, radiosonde observations over Boston, taken at 1330 EST, were also analyzed. This further provided information on the general wind conditions aloft during the middle period of the squall line.

In the case of the airmass thunderstorms the wind data will not be as representative of the conditions over the regions of storm occurrence; since these storms are much scattered and occurred at various times during the day.

The wind data are summarized in tables 3 and 4 for the two days respectively.

E. Definitions of Cells, Storms and Echo Line

It is appropriate here to define the terms cells, storms and echo line, on the basis of what the radar sees and as used in this study. It is realized that this is somewhat arbitrary, but such definitions are necessary in order to make meaningful deductions from the results of the analysis. The line is defined as the entire entity presented by the radar, and it may be solid or composed of a group of storms. Very small spots which appear to be at the limit of the radar's resolution will be regarded as cells. On the radar scope, these would range from about one to five miles in diameter. Echoes whose dimensions are between five and fifteen miles will be called storms. These definitions, given to cells and storms would seem to differ only in their size.

Sometimes a storm, as defined, is observed to contain more than one cell at a time, and sometimes it contains several cells in sequence.

For the purpose of describing such occurrence, storms are labelled by one of the letters of the alphabet and the individual cells labelled with the same letter but with numerical subscripts.

It was noted that fairly large portions of the squall line were displayed at intensity level 4; small areas, of the dimensions corresponding to "storms" as described above reached level 5, while a few isolated spots were recorded at level 6. Therefore the criterion for identifying an echo in this line as an intense echo was that it should reach intensity level 5. This corresponds to log Z_e equal to or greater than 4.5, or to a rainfall rate of about 30 mm/hour.

F. Methods of Analysis

Continuous PPI intensity maps for the squall line were displayed on a film viewer and traced on to standard sized maps (PPI image enlarged to 9 inches). These maps were constructed for every three minutes - a period through which all the seven intensity levels were photographed. This tracing was carried out from 1214 EST (when the first echo of the line appeared) to 1618 EST, when the line had moved directly over the radar site. Figure 5 shows examples of these maps. These tracings could then be superimposed so that motions and changes in structure of the entities within the squall line can be easily observed. Actually, the tracing was performed mainly to enable the author to follow the overall development of the line and to describe the evolution of new storms. Also it was possible by this means, to locate regions of greatest intensity within the line and their variations with time. Direct tracking of individual cells was made on the viewer as this eliminates the error that would be encountered in superimposing the former tracings.

Since the primary aim of this study is to observe the behavior of the more intense storms within the line, tracings were made of successive intensity level 5 (which is required by the criterion set out in section E above). This gave tracks of the motion of intense cells within the line. Because of the 5 db resolution in intensity a cell might disappear and reappear later, and some judgement had to be exercised in deciding whether it was still the same cell. Whenever such a break occurred, a lower intensity level would be examined to see whether the cell still continued at such a level or had actually disappeared during the break. If it still occurred at a lower level it was traced at that level and the appropriate intensity was noted for the eventual purpose of describing the variation of intensities within the cells. Also where level 5 showed a rather broad echo, the next higher levels were examined so as to keep track of any cells within the storm being followed.

The next step was to locate, in these tracks positions of new cell development. If a cell is small or if its reflectivity does not exceed that of the surrounding precipitation by at least 5 db, it might not appear explicitly on the maps but its existence can sometimes be inferred from small perturbations in the shape and/or motion of the storm which is being tracked. As an aid to locating new cell development, a distance-time chart was sketched for each storm track. From these charts, it could be seen that generally the cells did not exhibit any erratic behavior. Where a jump occurred in the chart or where the distance-time chart showed some inconsistency, new development was suspected. Fig. 6 shows some of the storm tracks and the corresponding distance-time charts. However, there is still some measure of subjectiveness in these analyses.

All the storm tracks were then presented on a single map in order to see the general pattern of the motions of the cells in relation to the movement of the entire line. The number of cells in each storm tracked and their duration were noted. The speeds of the cells were then computed by assuming uniform motion.

Some RHI film records of the squall line were also traced and identified with the corresponding cells that had already been traced from the PPI.

In order to see if there are any significant differences in the behavior of these storms and those of air mass type, a similar analysis was made of nine air mass thunderstorms that occurred at various times of August 28, 1965.

As far as these analyses are concerned, the accuracy achieved is subject to errors in the tracings when the image in the film is projected. Furthermore, the transfer of the radar pictures from film to tracing paper permits a possible error in geographical position. However, this kind of error is of little consequence to the results of this study. The most crucial factor that might reduce the accuracy of the analyses is in locating the position of new cell development. This is made more difficult by the poor resolution of the radar.

IV. RESULTS

A. Results of Raingauge Data

Analysis of raingauge data indicated that, as early as 0600 EST on August 19, 1965, there had been showery activity over some areas of New York State. But an organized line of precipitation did not emerge until about 1100 EST which, in any case, would indicate that the development of the squall line actually began before the first echo appeared on the radar scope. By 1300 EST this general line of rainfall had extended to parts of northern Vermont and Maine. The analysis further showed that the line extended all the way across Maine from 1500 EST onwards. Consequently the detailed analysis made from radar data were of the southern end of a squall line that appeared to be several hundred miles in length. The general eastward progression of this line as obtained from raingauge data is presented in fig. 7a. In this figure a small circle is shown at the location of each recording raingauge. The lines marked 1100, 1300, 1500, 1700 and 1900 EST indicate the general orientation of the squall line. The enclosed gauges were those that recorded 0.2 inches or more of rain during the hour ending at the indicated time. Because of the wide spacing of the raingauge network the squall line could not be presented as a continuous solid line. It may, however, be noted that raingauges close to the lines marked 1100, 1300 etc. in fig. 7a recorded 0.2 inches or more of precipitation at the indicated times.

Fig. 7b shows the corresponding radar picture of the general motion of the squall line. It could thus be observed from these figures that the pattern of the squall line as depicted by the raingauge network conformed with the radar pattern, at least qualitatively.

B. Overall Development of the Line as Shown by Radar

Initially the squall line appeared as a cluster of storms arranged in a line, but separated by a few miles. This was the case until about 1320 EST when two continuous lines emerged. At about 1340 EST a well defined and continuous line, about 130 miles long, had formed with increased intensity (fig. 8b). Shortly after this, it again broke into two main lines, with a few closely spaced clusters of storms. The least intense phase of the squall line occurred an hour after this with the main line reduced in length. At about 1600 EST the closely spaced clusters of echoes merged into a single solid line, about 200 miles long. This eventually moved over the radar site thirty minutes later. After this time, it was impossible to follow the subsequent development of the line because of the shadow created by ground objects close to the radar site. A graphical representation of the variation of the rate of rain deposit with time is given in fig. 9.

C. Regions of Greatest Intensity in the Line

During the hours that the line was under observation, the most intense portion of the line shifted from the upper end to the lower. Upper end here implies the upper end of the section of the squall line presented by the radar. (In all further description of the squall line, attention will be focussed only on the section of it that appears on the radar.) Fig. 8 (a-d) illustrates this general shift in the region of greatest intensity along the line. It was not, however, a steady and continuous effect.

The area of greatest intensity first observed in the line was its upper half. This was the case until about 1340 EST after which the area of most intense precipitation shifted to the middle of the line. Twenty minutes later the general area of intense storms was again observed to be the upper half, but the most intense cores were still concentrated in the middle of the line. At 1530 EST when the line had broken into three distinct entities, the bottom entity started to acquire great intensity but the most intense cores still lay within the upper two parts. Shortly afterwards, the intense areas were more or less evenly distributed throughout the entire line. By 1600 EST the area had shifted entirely to the bottom third of the line. An hour later the area extended to the lower half, a position which was maintained until the squall line came over the radar site, after which its progress was no longer followed.

The general pattern of the shift of the area of greatest intensity in the line as described above indicates that while new development took place towards the southern end of the line, simultaneous dissipation was occurring at the northern end. This result is in agreement with what Cochran (1961) observed in the squall lines he studied.

D. Storm Development within the Squall Line

The first echo of the squall line appeared at 1214 EST on the radar scope, about 120 miles northwest of the radar. Three echoes had formed by 1230 EST and these were in a line and separated by a few miles. Within the next 40 minutes these echoes had increased in number and still formed a line. Up to this time, the echoes reached only intensity level 4. The histories of the storms which reached intensity level 5 follow.

1315 EST - Storm A, the first intense storm appeared in the northernmost part of the line. It maintained intensity level 5 up to 1321 EST, after which it dropped to level 4. It finally decayed at 1341 EST.

1337 EST - Storms B and C appeared at this time. B appeared around the middle of the line and lasted until 1505 EST. It consisted of a series of cells each of which decayed as a new one developed. Storm C formed to the north of the line but below A. It was rather shortlived.

1341 EST - Storms D, E, F, G and H formed at this time, all spaced along the line, with the exception of H which formed ahead of the line and to the north of it. Storm D lasted till about 1400 EST, while E, F, G and H continued for quite a while, each lasting more than one hour.

1347 EST - Storm I appeared to the bottom of the line. It lasted more than one hour.

1357 EST - Storm J formed further south of the line. It was rather shortlived.

1417 EST - three storms, K, L and X appeared. K and L formed to the south of the line, while X formed to the north of it. K lasted about 40 minutes while X and L each lasted more than an hour.

1429 EST - Storm M appeared at this time. Half an hour later it merged with another echo and intensified during the next few minutes. It lasted more than one hour.

1503 EST - Storms N and O formed, N in the northernmost part of the line and O near the bottom of the line. Both persisted for some time.

1520 EST - Storms P, Q and S appeared at about this time. Specifically P appeared at 1517 EST; Q at 1530 EST and S at 1515 EST. P formed to the north of the line; S to the middle and Q to the south of the line.

1540 EST - Storm T formed to the north of the line and lasted for only a short time.

1600 EST - Storm R appeared to the south of the line and it was very shortlived. At about this time quite a few storms developed around the middle of the line, apparently after the storms which formed earlier had decayed. These storms were of relatively shorter duration than those which formed to the north and south of the line.

E. Description of the Life History of Individual Cells

Some of the storms listed in the previous section apparently contained one cell while others consisted of a sequence of cells. In this section the life history of each cell is described; much of the information is summarized in table 5, and in fig. 10. All times are expressed in Eastern Standard Time (EST).

Storm A - The first echo of cell A appeared at intensity level 4 at 1249. It maintained this intensity until ti decayed at 1315, giving rise to a new more intense cell A1 which appeared at intensity level 5. This new cell was formed above the decaying cell, and it maintained its intensity until 1321 after which it dropped to level 4. Cell A1 showed up at level 5 at 1338, dropping to level 4 three minutes later. It finally decayed at 1341 with no new cell formed.

Storm B - cell B formed at 1337, showing up at level 5. At 1341 a new cell B1 appeared below the old cell. The new cell maintained intensity level 5 until 1357 when it intensified to level 6. It dropped to level 5 again at 1359, finally decaying at 1401. A new cell B2 formed immediately after B1 had dissipated. Cell B2 broke into two at 1407 - the lower one dissipating at 1413. The upper cell continued until 1419, when a new cell B3 developed. At 1431 B3 decayed and cell B4 appeared. Due to interruption (caused by transfer of radar to RHI scan) it was not possible to follow, with any degree of certainty, the motion of cell B4. However, it seemed to have intensified to level 6 at 1451 and four minutes later, merged with another storm just below it.

Storm C - Cell C appeared at 1337 with intensity reaching up to level 5. Ten minutes afterwards it dropped in intensity to level 4 and at 1351 returned to intensity level 5. It maintained this intensity till 1355 after which it decayed without a new cell forming.

Storm D - Frequent interruptions did not permit its life history to be followed accurately.

Storm E - The first cell in storm E began at 1341 at level 5, an intensity which it maintained throughout until its decay at 1407. A new cell formed immediately after cell E had decayed. This new cell immediately dropped to level 4 and eventually merged with the lower intensity level so that its subsequent history could no longer be traced.

Storm F - This actually started at intensity level 4 at 1313. It continued at this intensity until 1339 after which a new cell F1 formed. Cell F1 immediately increased in intensity to level 5 until 1347 when it further increased to level 6. Ten minutes afterwards its intensity dropped to level 5. At 1401 cell F1 broke into three cells. The lower two of these three cells decayed at 1411 while the upper cell, F2, continued. This maintained level 5 intensity until 1429 when it intensified to level 6. It decayed shortly afterwards. A new cell F3 formed below cell F2 at about 1444 reaching intensity level 6. It maintained this intensity up to 1459 after which it dropped to level 5. It finally decayed at 1503, with no new cells formed.

Storm G - This storm appeared at 1345 reaching only intensity level 4. It intensified to level 5 shortly before it decayed at 1349 with a new cell G1 forming. Cell G1 rapidly intensified to level 6, an intensity which it maintained for only five minutes. It dropped in intensity to level 5 and finally decayed at 1411 after which a new cell G2 formed. Cell G2 intensified to level 6 at 1415, returned to level 5 at 1421 and finally it decayed at 1425 with a new cell forming below it. The new cell dropped in intensity to level 4 and merged with another storm, so that its further progress could not be determined.

Storm H - Storm H merged with a storm complex soon after it formed. Hence its life history could not be accurately described.

Storm I - The first cell of this storm began at level 4 at 1335. It maintained intensity level 4 until it dissipated at 1347 after which a new cell I1 formed. Cell I1 immediately intensified to level 5 and at 1353 it further intensified to level 6, which it maintained until 1401, dropping to level 5 again. It finally decayed at 1419 with a new cell I2 forming close to it. The cell I2 showed up briefly at level 6 before dropping to level 5 - an intensity which it maintained until it decayed at 1431. A new cell I3 formed immediately after this. Cell I3 continued at constant intensity level 5 until it finally disappeared at 1457 with no more new cells forming.

Storm J - Cell J first showed up at level 4 at 1341. It continued at intensity level 4 until it decayed at 1355 with a new cell J1 forming. At 1337 J1 intensified to level 5. This it maintained until it disappeared at 1405. A new cell which later formed after J1 could not be followed accurately because of interruption by RHI.

Storm K - Cell K formed at intensity level 4 at 1401. It continued as shower until 1415. Two minutes later, a new cell K1 appeared below cell K at intensity level S. It dropped in intensity to level 4 at 1423 and continued at this intensity until it decayed at 1437 with a new cell K2 appearing. Cell K2 intensified to level 5 by 1455, dropped to level 4 at 1457 and decayed immediately afterwards. A new cell formed below K2 at 1457 at intensity level 4, but this decayed at 1505 without a new cell forming.

Storm L - This storm began at intensity level 4 at 1413. Four minutes later, it intensified up to level 5. It continued at this intensity until 1429 after which it dropped to level 4. It finally dissipated at 1431 with no new cell forming afterwards.

Storm M - The first cell appeared at level 5 intensity at 1429. A few minutes later it dropped to level 4 and at 1437 a new cell M1 formed. Cell M1 maintained a constant intensity level 5 until it decayed at 1453 with a new cell M2 appearing. Two minutes later M2 merged with an echo above it and then intensified to level 6. By 1511 two cells had emerged from cell M2. The reason Storm M did not appear in fig. 10 is that its position is within the general area of storms L and F.

Storm N - Storm N began at intensity level 4 at 1501. This cell intensified to level 5 between 1503 and 1507, after which it dropped in intensity to level 4. It continued at this intensity until it dissipated at 1523 with a new cell appearing. This latter cell could not be accurately tracked owing to the interruption of the PPI scan by the RHI.

Storm O - Storm O developed as a shower reaching level 4 intensity at 1459. The cell then intensified to level 5 at 1503 and maintained this intensity until 1519 when it finally decayed. The film was interrupted at this time. At 1530 a new cell O1 appeared at intensity level 5. Cell O1 continued at this intensity until it decayed at 1550. A new cell formed immediately after cell O1 had disappeared, but could not be followed because it was indistinct.

Storm P - As soon as this developed at 1517, it went up to intensity level 6. After 1530 its intensity dropped to level 5. Six minutes later it broke into two distinct cells. The upper cell P1 maintained a constant intensity level 5 until it decayed at 1554. A new cell which formed afterwards could not be accurately followed.

Storm Q - It appeared at 1530 reaching intensity level 5. It continued at this intensity until it dissipated at 1558 with a new and more intense cell forming near it. Because of interruption, this new cell could not be followed.

F. Vertical Sections Through Cells F2, F3 and G

RHI photograph taken at 1446 EST, azimuth 297 degrees and range of 100 miles showed the vertical section through the southern end of cell F3. In this picture shown in fig. 11a, two well-defined peaks can be observed, suggesting the presence of another cell, possibly the dying stage of cell F2. At this time the indicated height of the cells was 22,000 feet with intensity reaching up to level 5. The RHI picture in fig. 11b taken at 1450 EST and at azimuth 303 degrees, was through the most intense portion of cell F3, with an indicated height of a little over 25,000 feet. Fig. 11c shows RHI photograph of a section through cell G taken at 1448 EST and azimuth 321 degrees. Apparently this was taken towards the dissipating stage of the cell. It reached an apparent height of about 20,000 feet.

In all these photographs, the cells showed a well-defined vertical structure. However, their heights, as given by the radar, cannot be taken as representing the true heights, due to the fact that they were all at a considerable distance (over 70 miles) away from the radar site. Because of the large beam width of the SCR 615-B radar, the volume sampled at great ranges becomes large and the top of the storm may not correspond very closely to the top of the echo. In this case the minimum detectable signal can go up as high as level 3 or 4, with the result that not all the signals returned at lower intensity levels are received.

A section through the line at 1708 EST and azimuth 290 degrees (fig. 11d) showed this portion of the squall line as reaching up to 40,000 feet. This does not mean that this section reached a truly greater height than the cells F2, F3 and G in view of the explanation given above. In this case the indicated height will be close to the true value since the squall line was now close to the radar.

G. Analysis of the air mass thunderstorms

Air mass storms selected were those that occurred at various times on August 28, 1965. Fig. 12 indicates the general locations of some of these storms. Here the storms are labelled with Roman numerals and the cells with alphabetical subscripts. Much of what is described in this section is summarized in table 6, and the storm tracks are shown in fig. 13. It is to be noted here that the storms were too scattered for raingauge data to be of any use.

Storm I - This storm appeared when the radar was turned on at 1220. It intensified to level 5 a few minutes after its formation. It continued at this intensity level until the radar was turned off for RHI at 1235. This storm did not appear again when the radar was turned on at 1251. Thus it was not clear whether the storm continued further after 1235 or decayed thereafter. However, from the changed configuration of this storm at 1235, it might be concluded that it was reaching the end of its life at this time.

Storm II - Storm II appeared at 1251 reaching intensity level 6, two minutes later. It maintained this intensity until 1311 after which the new cell IIa developed. This new cell intensified to level 7 almost immediately after it was formed. Five minutes later it further intensified to level 9. At 1323 it dropped to level 6 intensity, rose again to level 8 at 1330, maintaining this intensity until the time of its decay at 1333. A new cell seemed to form above it at this time, but the interruption (caused by shift to RHI scan) did not permit further track of this cell. The distance-time chart of this storm showed sufficient consistency with Storm I to suggest that it might be the continuation of Storm I. Nevertheless the circumstance of the fact that the PPI scan was interrupted made it difficult to reach a definite conclusion about its time of formation.

Storm III - The first cell of this storm formed at 1253 reaching up to intensity level 6. This dropped to level 5 at 1300. It continued at this intensity until it dissipated at 1307, with a new cell IIIa forming immediately afterwards. This new cell immediately intensified to level 6 and maintained this intensity until 1318 when it dropped to level 5. Cell IIIa finally decayed at 1326, with no new cell formed.

Storm IV - This storm developed at about 1430 with its intensity reaching level 5. This dropped to level 4 five minutes later. The intensity further dropped to level 3 at 1444 after which it disappeared.

Storm V - Storm V appeared on the radar scope at 1450. It maintained intensity level 5 up to 1520 after which it rose to level 6. It continued at level 6 until 1555 when it further increased to level 7. Five minutes later it dropped to level 6, and continued at this level until 1615 when it dropped to level 5 before finally disappearing.

Storm VI - The first cell formed at 1508 reaching level 6 intensity. This dropped to level 5 at 1520 and stayed at this level until 1530 after which it decayed and a new cell VIa developed. Cell VIa maintained constant intensity level 5 throughout its life history which ended at 1601. A new cell VIb which formed after cell VIa maintained intensity level 5 until it decayed at 1616 with another new cell formed. This new cell could not be tracked accurately because of interruption of the PPI for the RHI. However, it seemed to be short-lived as it did not appear again when the radar was turned on five minutes later.

Storm VII - This storm developed at 1542 with its intensity reaching level 5. This rose to level 6 ten minutes afterwards. At 1605 it broke into two cells which later merged to form cell VIIa at 1612. Cell VIIa intensified to level 6, and at 1636 it further went up to level 7. It continued at level 7 until 1647 when it broke into two. The lower of these two new cells, denoted by VIIb continued at level 7 until 1708 when it finally disappeared.

Storm VIII - The first cell of Storm VIII appeared at intensity level 5 at 1629. This intensified to level 6 at 1642, dropping again to level 5, five minutes later. It eventually decayed at 1653 with no new cell formed.

Storm IX - Storm IX formed at 1631 having intensity up to level 5. It maintained this intensity level throughout its life history. The cell finally disappeared at 1739, lasting an hour and a few minutes.

One interesting development in these air mass storms is the tendency for some storms to follow the same track as others which had formed earlier. For example, Storm IX which formed at 1631 followed almost identical track as Storm V which began at 1450. No explanation is offered for this behavior of the storms.

Fig. 14 shows vertical sections through storms I, III and VI as presented by the RHI. Storms I and III showed two peaks, suggesting the possibility of two cells for each of them. These storms showed well-defined vertical build up just as was observed in some of the squall line cases. Storm VI tilted a little away from the vertical, reflecting the effect of environmental winds.

H. Cell Motions in Relation to the Wind Field

Examination of table 3 shows that, for the squall line day of August 19, 1965, the general wind direction between 850 and 500 mb was between 220 and 240 degrees for the three stations at 0700 EST. This general direction was around 240 degrees at Nantucket at 1900 EST. The direction of motion of the cells in the squall line ranged between 231 and 270 degrees (see table 5). In particular, of the 43 cells tracked, 8 moved in a direction between 230 and 240 degrees, while the rest moved between 240 and 270 degrees. Thus, a large majority of the cells moved in a direction to the right of the wind by as much as 0 to 30 degrees. It is interesting to note that the environmental winds obtained from the radiosonde data agree fairly well with the horizontal wind velocities obtained by Donaldson, Jr., Armstrong and Atlas (1966), in their doppler measurements of horizontal motions in the same squall line that was studied here. Further more a large number of the cells within the squall line moved with speeds greater than the wind speed between 700 and 500 mb.

The motion of the cells of the air mass storms exhibited a different behavior from those of the squall line cells. Here these cells were observed to move generally to the left of the wind. While the general wind direction was between 250 and 270 degrees, only four of the fifteen cells tracked had directions in this range; the rest moving to the left of 250 degrees. Also the cells here moved with lesser speeds than the general upper level wind speed. However, this result cannot be regarded as conclusive of this behavior since the storms were too scattered and mostly far away from the radiosonde stations. In addition to this, the storms appeared at various times which were different from the times the upper level wind observations were made.

V. DISCUSSION OF RESULTS

The analyses show that the development of the storms within the squall line is towards a southerly end. These developments are not in perfect sequence, but rather, they appear in groups. This is in agreement with the results obtained by Cochran (1961). The largest group of the more intense storms (B,C,D,E,F and G), all appear nearly simultaneously around 1340 EST, presumably encouraged by a diurnal heating effect, and they are all to the south of Storm A, which previously had been the most intense storm. The appearance of this group might also have been influenced by topography as they are in or just east of Connecticut River Valley.

A. Cell Development

Squall line case: The storms can be classified into two major groups, according to the nature of cell development within them. The first group are those in which the number of cells formed during their life times are precisely known. In the second group, it is not possible to ascertain exactly how many cells were formed because they later lost their identities.

The first group can be further subdivided into four categories according to the number of cells in each of the storms:

(a) Single-cell storms - Storms C and L come under this category

(b) Storms with two cells - Storm A is the only one having two cells

(c) Storms with three cells - here we have Storm M

(d) Storms with four cells - under this division we have the two storms F and I.

Thus of the 15 storms actually followed, only 6 have precisely known number of cells, the remaining 9 falling into the second group. Also further subdivision of this second group (according to the number of cells formed before they lose their identity) yields the following:

(a) Storms E, N and Q were observed to have two cells each. In each of the storms, the life histories of the first cells were obtained while this was not possible for the second cells because they merged with neighboring storms.

(b) Storms J, O and P each have a sequence of three cells before they subsequently lose their identity.

(c) Storms G and K no longer maintain their identity after forming a sequence of four cells.

(d) Storm B has a sequence of five cells after which it could no longer be followed. In all the cases (b) to (d) the complete life histories of the last in the sequence of cells could not be obtained, because each of them merged with other storms in the line.

The above results clearly indicate that the intense storms within the squall line consist of a sequence of cells of relatively short lifetimes. Altogether there are 43 cases of cell development, out of which 15 are terminal, of the remaining 28, as many as 23 show tendencies for new cells to form close to the bottom right of old cells. Only in four cases do we have new cells forming close to the upper right of decaying cells; while in one case the storm ends its life by breaking up.

Air mass storms case: The cells of the air mass storms exhibit essentially similar patterns of development to those of the squall line. Two of the 9 storm cases analyzed (Storms V and IX) are of relatively long duration, each lasting more than one hour; and they each consist of single cells. Storms I, IV and VII also have single cells each, but they are rather shortlived. Storms II and III have two cells each, while Storms VI and VII each have three. Furthermore, the behavior of these air mass storms regarding the preferred position of new cell development, parallels that of the squall line; the majority of new cell formation occurs close to the bottom right of old cells.

These cell developments are quite in agreement with what Chisholm (1966) found in his study in which there were several new cell developments clustering around old cells; the most favored region of new cell development is close to the bottom right of old cells. Thus both the result of the present study and that of Chisholm confirm Byers and Braham's (1949) suggestion that new cell growths occur in the vicinity of decaying cells, although Byers and Braham did not specify exactly the most preferred position of the new cells relative to old cells. Also, the tendency for the new cells to form mostly close to the bottom right of old cells seems to agree with the dynamical explanation of the development of new storm cells which is offered by Newton (1960) in his cumulonimbus model (see again fig. 3). In this model Newton stresses the important role of wind shear in intensifying the convection and causing continual regeneration of new growth on the forward right flank.

B. Cell Duration

The durations of the cells in the squall line storms range between 4 and 30 minutes, with the largest group of cells having duration between 15 and 20 minutes. The corresponding range in the case of the air mass storms is much wider, this being between 10 and 90 minutes, with majority falling in the 20-25 minutes range. Thus the cells in the air mass storms last much longer than those in the squall line. It should be emphasized, however, that this is not a difference in the characteristics of the two types of storm; rather, they are related to the particular storm regardless of whether it is air mass storm or squall line storm. Fig. 15 shows histograms of cell durations in the two cases. These results are in complete agreement with values obtained by Battan (1953). Quite recently Chisholm (1966) has observed similar radar life times for individual cells of thunderstorm echoes.

The overall durations of each storm in the squall line are between 30 and 90 minutes, with majority of them showing preference for 60-minute duration. These durations are obviously in the lower range of thunderstorm life times, which is not surprising when it is realized that these storms though intense, are not what might be called severe storms.

C. Cell Motion

All the cells tracked in the squall line move in a direction which is clockwise from the axis of the line. This result confirms what Byers and Braham (1949) observed in the squall lines they studied. Only a few of the cells move with velocities between 20 and 30 mph.

Most of the cells move faster than the entire line, whose speed was estimated to be 22mph.

In the case of the air mass storms, the speed of motion of the cells ranges between 30 and 40 mph. This agrees with what Browning and Ludlam (1960) obtained in their study of Workingham storms.

While the cells of the squall line storms move faster than the upper level wind and to the right of the winds, those of the air mass storms moved mostly slower than, and to the left of upper level winds. However, this apparent difference in the cell motions is not to be taken as significant, since storms of the same type can exhibit such differences depending on such factors as their environmental wind field.

D. Further Remarks

One important question which the results of this study could not account for is the existence of relatively large areas of less intense echo which are found in between the more intense echoes within the squall line. Such areas do not show up in the air mass storms. Various explanations have been offered to account for the presence of such areas. For example, it has been suggested that these areas of less intense precipitation could possibly represent the areas of influence of the intense updrafts within them. A flaw in such an explanation is the fact that air mass storms can just be as intense as squall line storms and yet no such "areas of influence" are present in the air mass storms. On the other hand, such areas might be made up of the small less intense cells which are not observable due to the limitation in the radar resolution. From a synoptic viewpoint, such areas could be part of a general area of lifting in the vicinity of the front, while the strong cells represent regions where the instability is released.

Hitschfeld (1960) has observed that parts of a storm, which is in severe vertical wind shear, appears to be carried by the wind, forming extensive plume patterns which trailed down toward the ground while evaporating. Hitschfeld's analysis showed that the particles of the plume were of precipitation size. [The work "plume" was used by Hitschfeld to denote the considerable over-hang which cumulonimbus develops as a result of strong wind shear.] Thus this erosion of convective clouds is purely a radar phenomenon and it is to be distinguished from cloud anvil whose particles are not of precipitation size. There is therefore the possibility that these areas of less intense echoes might be a consequence of such plumes reaching the ground as precipitation. However, the air mass storms studied here showed just as much wind shear without occurrence of any areas of less intense radar echoes.

VI. CONCLUSION

From a single case study, the structure and behavior of the more intense storms in a squall line have been investigated, using radar data which were in the form of range-normalized signal intensity maps. Life histories of storms (any area with log Z_e greater than 4.5) and of individual cells (intense echoes smaller than five miles in dimensions) were considered both for a highly organized squall line and a group of scattered air mass storms. Raingauge data were also analyzed for the squall line day, while records of available upper level winds were examined for both days.

In both cases, the squall line and the air mass storms, it was found that most of the storms were comprised of a sequence of cells of relatively short lifetimes, the most frequent being on the order of 20 minutes. Thus, in general, the mode of development is a sequence of cells of Byers and Braham (1949) type rather than a single long-lasting one of the Browning and Ludlam (1960) variety. This, of course, does not imply that the Browning and Ludlam model is not correct; it is just that their model does not apply to most of the storms studied here. Only by such studies as this, can this fact be brought out since on a mesometeorological scale, the pattern of development of such storms as studied here would appear to be more or less steady state. Furthermore, the results of this study firmly establish the fact that the most favored position of new cell development for both cases is the bottom right of old cells. This should account, at least in part, for observed tendencies of storm complexes to move to the right of, and more slowly than, the prevailing wind.

The cells of the air mass storms were found to have relatively longer lifetimes and move much faster than those of the squall line storms. This is not surprising when it is remembered that the air mass storms were more intense and were in a stronger environmental wind field. Also, while most of the cells within the squall line moved to the right of upper level winds, most of the air mass storms were moving to the left of the winds. However, this difference cannot be regarded as peculiar to storm types; rather, they are differences that can exist in storms of the same type.

By and large, the behavior pattern of the squall ine storms was very similar to that of the air mass storms. The similarities are to be considered as significant because characteristics such as the pattern of cell development are then not peculiar to the particular storm or storm type.

From the available data it was not possible to learn anything concerning the nature of the areas of lighter precipitation within the squall line.

The three-dimensional structure of convective cells was not given maximum consideration in this study, partly because of lack of adequate RHI data. For example, RHI records of as many sections of the squall line as have intense storms might yield more information concerning the circulation (in the vertical) within these cells, that would explain the preferred position of new cell development. Such RHI observations of the storms could also enable one to see the extent to which wind shear affects the cell growth, with the ultimate aim of setting up more realistic storm models. However, with availability of more RHI data the instrumentation of the radar would still have to be improved for better radar resolution to provide a study of the internal structure of the cells within the storms.

Finally, it is suggested that similar investigations as made here should be undertaken for many squall lines so as to be able to arrive at conclusions that will be of statistical significance.

Table 1. Intensity Calibration (squall line)

Intensity Level	Log Z_e	Rainfall Rate in mm/hr
1	2.6	1.5
2	3.1	3
3	3.8	9
4	4.3	18
5	4.8	36
6	5.2	65
7	5.5	100

Table 2. Intensity Calibration (air mass storms)

Intensity Level	Log Z_e	Rainfall Rate in mm/hr
1	2.6	1.5
2	3.2	4
3	3.9	10
4	4.3	18
5	4.9	42
6	5.3	75
7	5.5	100
8	5.7	128

Table 3. Wind Data August 19, 1965

(dd/ff = wind direction/wind speed)

	Level (in mb)	Portland	Albany	Nantucket
0700 EST	850	220/25	230/20	220/27
	700	220/35	230/31	210/18
	500	240/38	240/35	220/25
	400	220/41	240/39	240/23
	300	230/54	240/45	170/25
	250	230/51	250/60	210/18
	200	250/59	250/55	270/15
1900 EST	850	No Report	320/09	220/08
	700	No Report	260/17	250/07
	500	250/45	260/24	230/12

Table 4. Wind Data August 28, 1965

(dd/ff = direction/speed)

	Level (in mb)	Portland	Albany	Nantucket
0700 EST	850	250/43	260/38	230/25
	700	240/41	250/51	250/46
	500	250/59	250/64	250/65
	400	250/60	250/62	250/74
	300	240/76	No Report	260/70
	250	240/87	No Report	250/70
	200	240/87	No Report	No Report
1900 EST	850	270/19	260/16	280/16
	700	290/27	270/25	290/29
	500	280/48	270/60	260/40
	400	250/56	260/57	250/46
	300	260/64	250/50	250/49
	250	260/70	260/66	260/68
	200	260/64	260/76	270/75

Table 5. Summary of Description of the Intense Storms within the Squall Line

Storm	Cells	Cell Duration mins.	Motion Speed mph	Motion Direction degs.	Location of new cells with respect to old cells	Start of cell EST	End of cell EST
A	A	26	25.4	257	top right	1249	1315
	A1	26	27.7	263	no new cell	1315	1341
B	B	4	37.5	239	bottom right	1337	1341
	B1	20	33.0	237	bottom right	1341	1401
	B2	18	33.3	241	bottom right	1401	1419
	B3	12	30.0	249	bottom right	1419	1431
C	C	18	20.0	236	no new cell	1337	1355
E	E	26	43.8	232	bottom right	1341	1407
F	F	24	25.0	270	top right	1313	1337
	F1	20	30.5	270	top right	1339	1359
	F2	28	32.1	264	bottom right	1401	1429
	F3	19	31.4	247	no new cell	1444	1503
G	G	4	30.0	231	top right	1345	1349
	G1	22	25.6	260	bottom right	1349	1411
	G2	14	34.1	254	bottom right	1411	1425
I	I	12	30.0	270	bottom right	1335	1347
	I1	32	24.0	260	bottom right	1347	1419
	I2	12	31.0	247	bottom right	1419	1431
	I3	20	27.0	247	no new cell	1431	1451
J	J	14	21.4	234	bottom right	1341	1355
	J1	8	22.5	237	bottom right	1355	1403
K	K	14	25.7	251	bottom right	1401	1415
	K1	20	30.0	252	bottom right	1417	1437
	K2	20	30.0	256	bottom right	1437	1457
L	L	18	33.3	242	no new cell	1413	1431
M	M	4	30.0	270	bottom right	1429	1433
	M1	14	25.7	248	bottom right	1437	1451
	M2	31	31.4	246	broke into two	1453	1524
N	N	22	32.7	242	bottom right	1501	1523
O	O	20	30.0	245	bottom right	1459	1519
	O1	20	30.0	249	bottom right	1530	1550
P	P	17	31.8	252	broke into two	1517	1534
	P1	18	33.3	234	bottom right	1536	1554
Q	Q	28	21.4	263	bottom right	1530	1558

Table 6. Summary of Description of the Air Mass Storms

Storm	Cells	Cell duration mins.	Motion Speed mph	Motion Direction degs.	Location of new cells with respect to old cells	Start of cell EST	End of cell EST
I	I	13	32.1	249	no new cell	1222	1235
II	II	20	33.0	250	bottom right	1251	1311
	IIa	22	32.7	263	top right	1311	1333
III	III	14	34.2	241	bottom right	1253	1307
	IIIa	19	34.6	242	no new cell	1307	1326
IV	IV	14	34.2	237	no new cell	1430	1444
V	V	85	42.4	247	no new cell	1450	1615
VI	VI	22	40.9	243	bottom right	1508	1530
	VIa	30	40.1	235	bottom right	1530	1601
	VIb	15	40.0	243	bottom right	1601	1616
VII	VII	23	36.6	256	broke into two	1542	1605
	VIIa	35	42.8	250	bottom right	1612	1647
	VIIb	21	40.0	249	no new cell	1647	1708
VIII	VIII	24	37.7	248	no new cell	1629	1653
IX	IX	68	44.0	247	no new cell	1631	1739

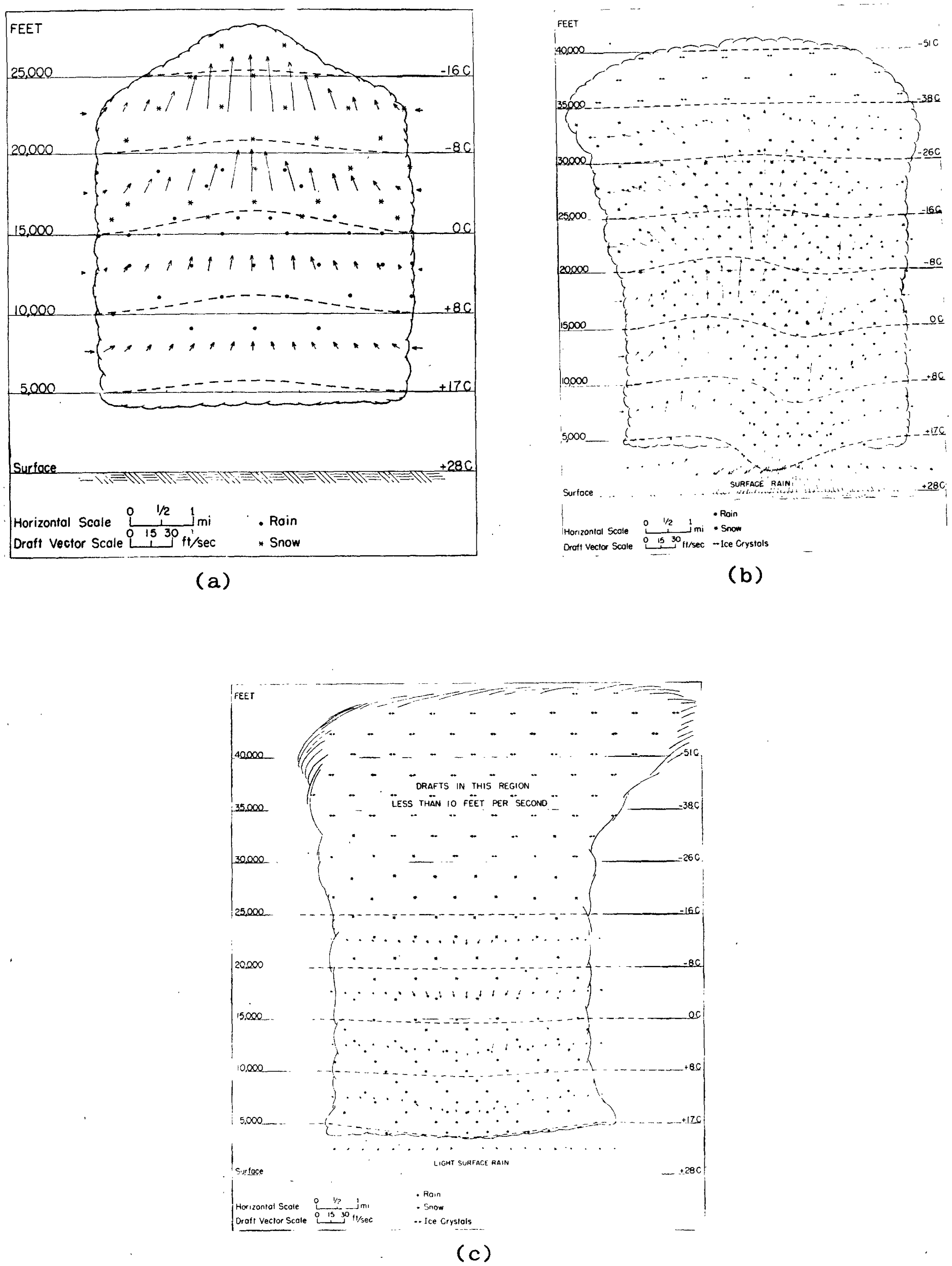


Fig. 1 Idealized cross-sections through a simple thunderstorm cell. (a) Cumulus stage; (b) Mature stage; (c) Dissipating stage. [After Byers and Braham, 1949]

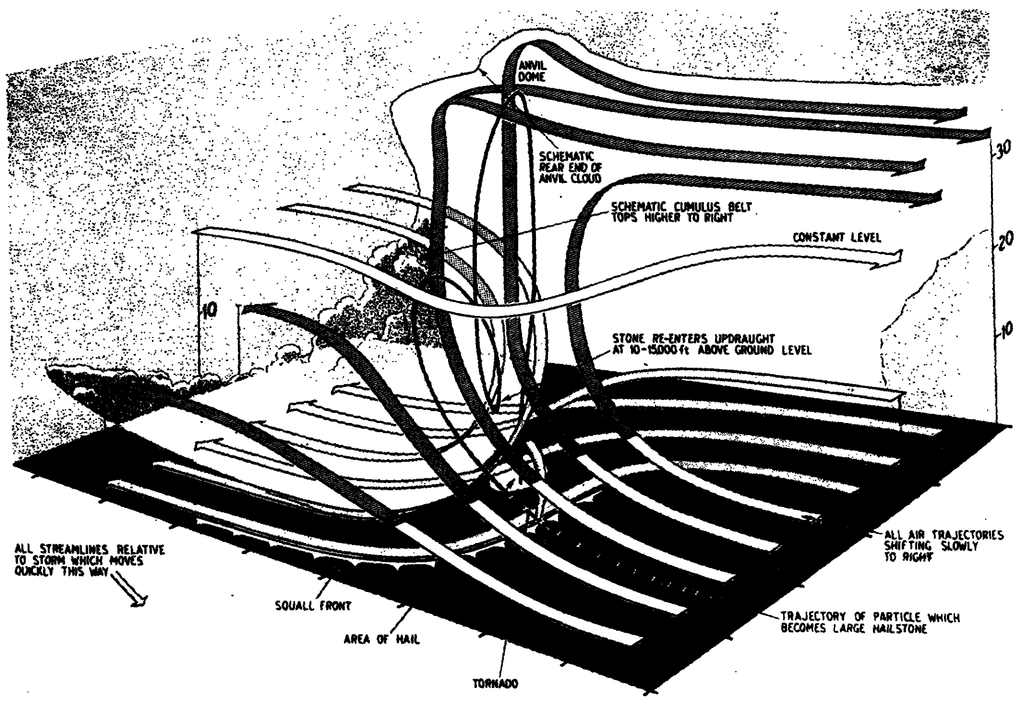


Fig. 2 Three-dimensional model of the Workingham storm.
[After Browning and Ludlam, 1962]

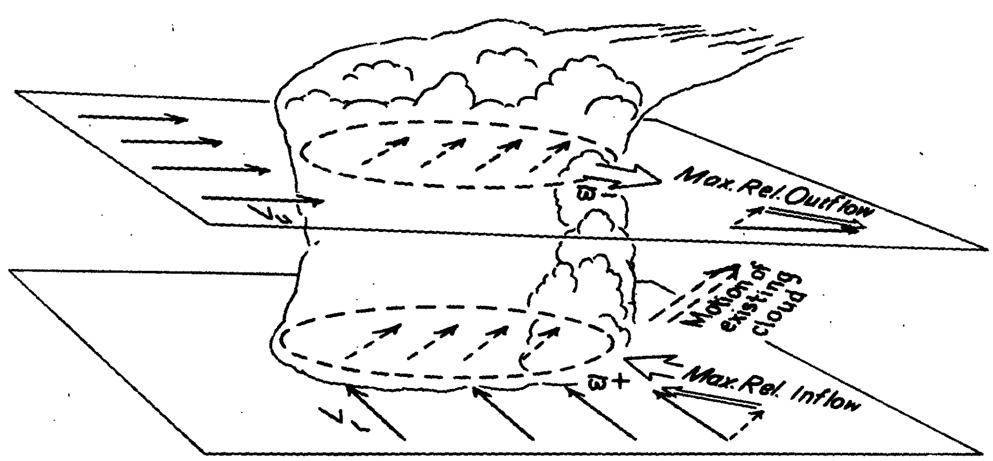


Fig. 3 A large isolated thunderstorm element imbedded in an environment in which the wind veers with height.
[After Newton, 1960]

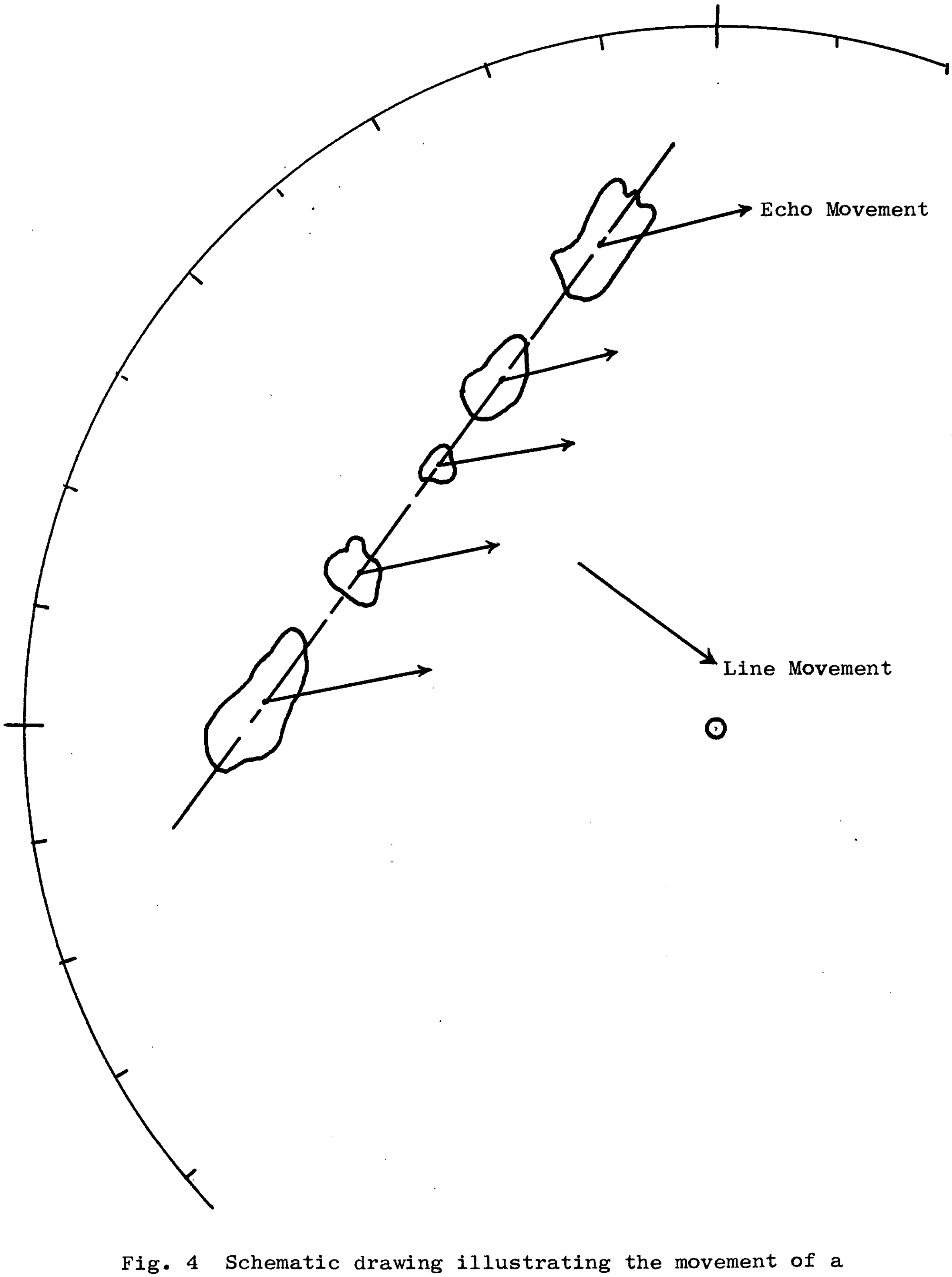
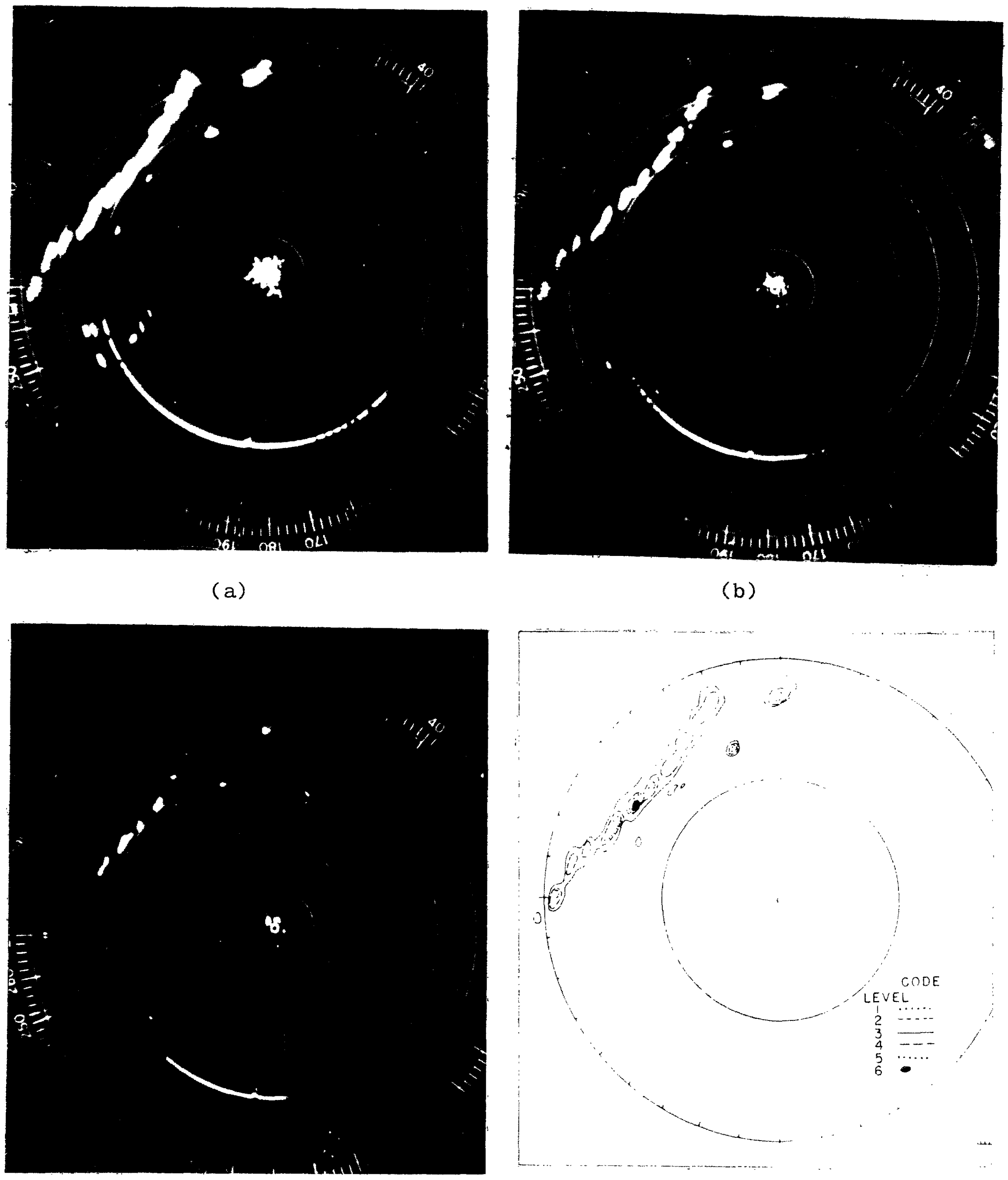


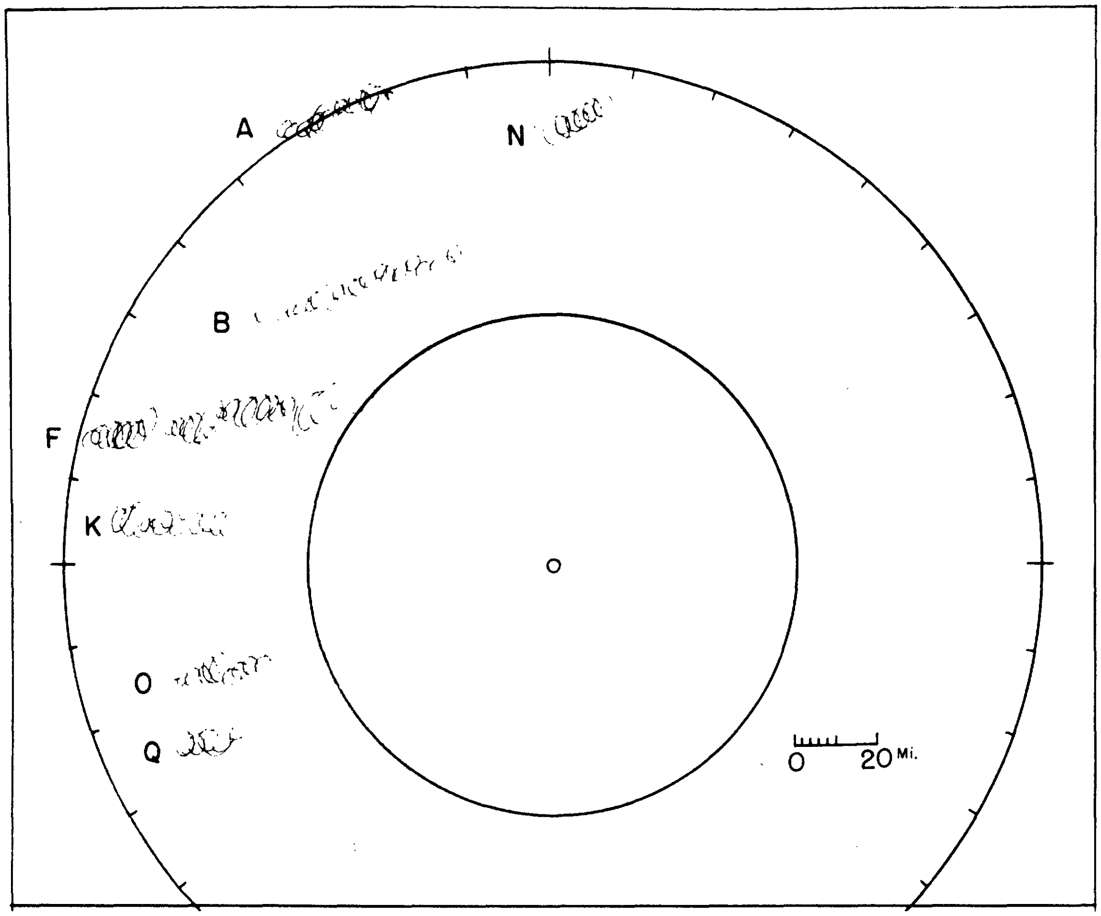
Fig. 4 Schematic drawing illustrating the movement of a squall line and the individual echoes in the line.



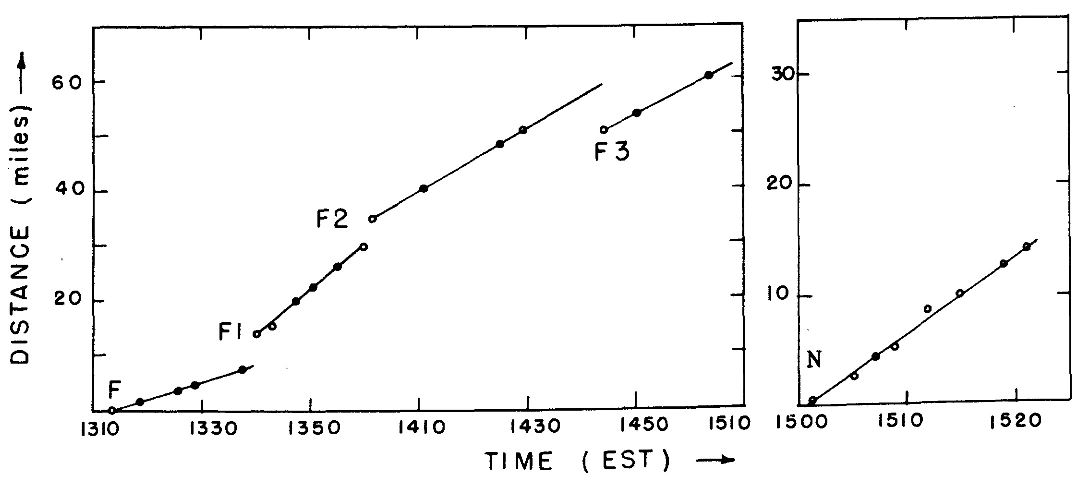
(a) (b)

(c) (d)

Fig. 5 Example of radar data for the squall line at 1400 EST. Photographs (a) - (c) show intensity levels 2, 4 and 5, respectively. Map (d) shows the complete tracing.



(a)



(b)

Fig. 6 (a) Tracks of some of the intense storms in the squall line.
(b) Distance-time charts for storms F and N.

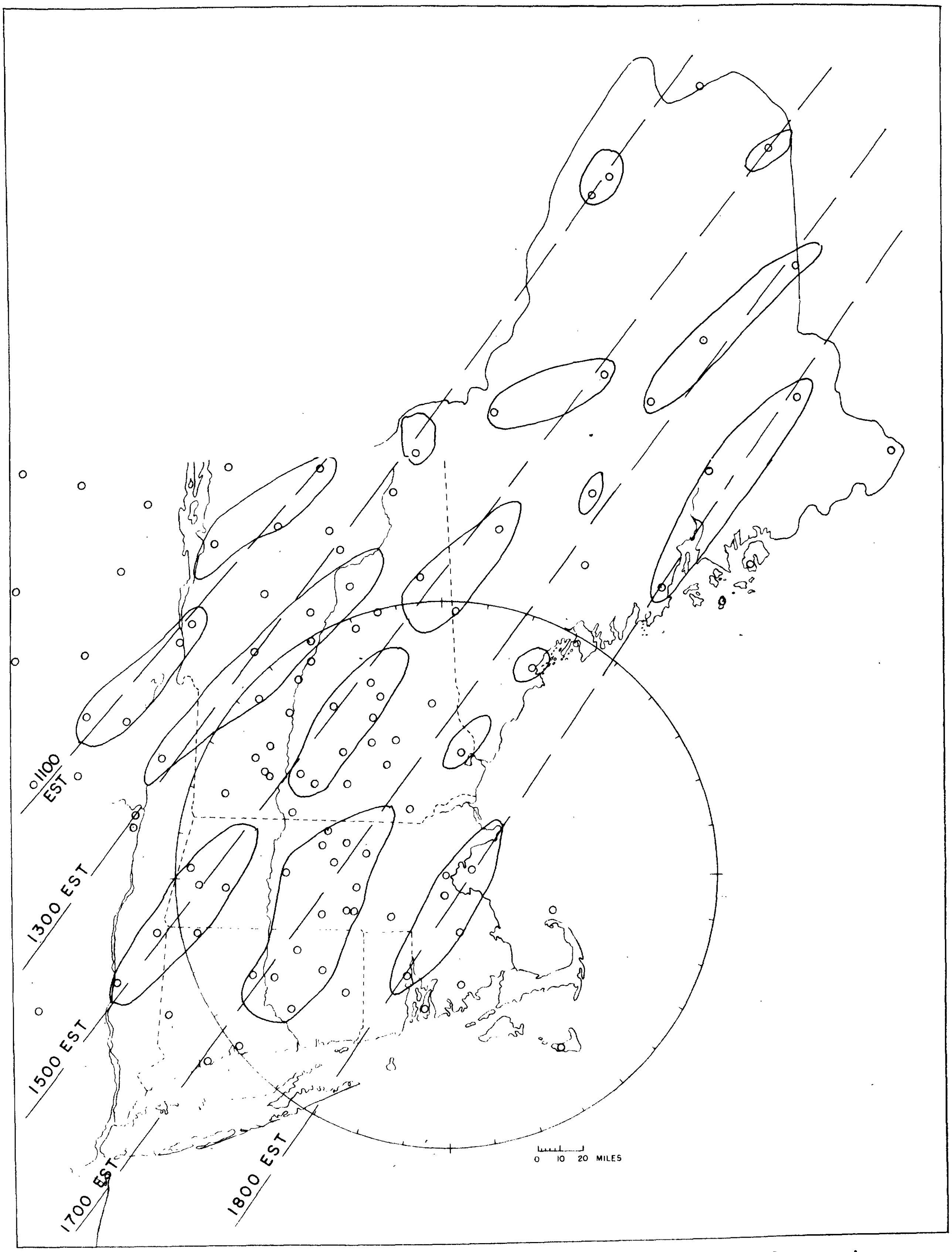


Fig. 7a General progression of the squall line as obtained from raingauge network. (see text)

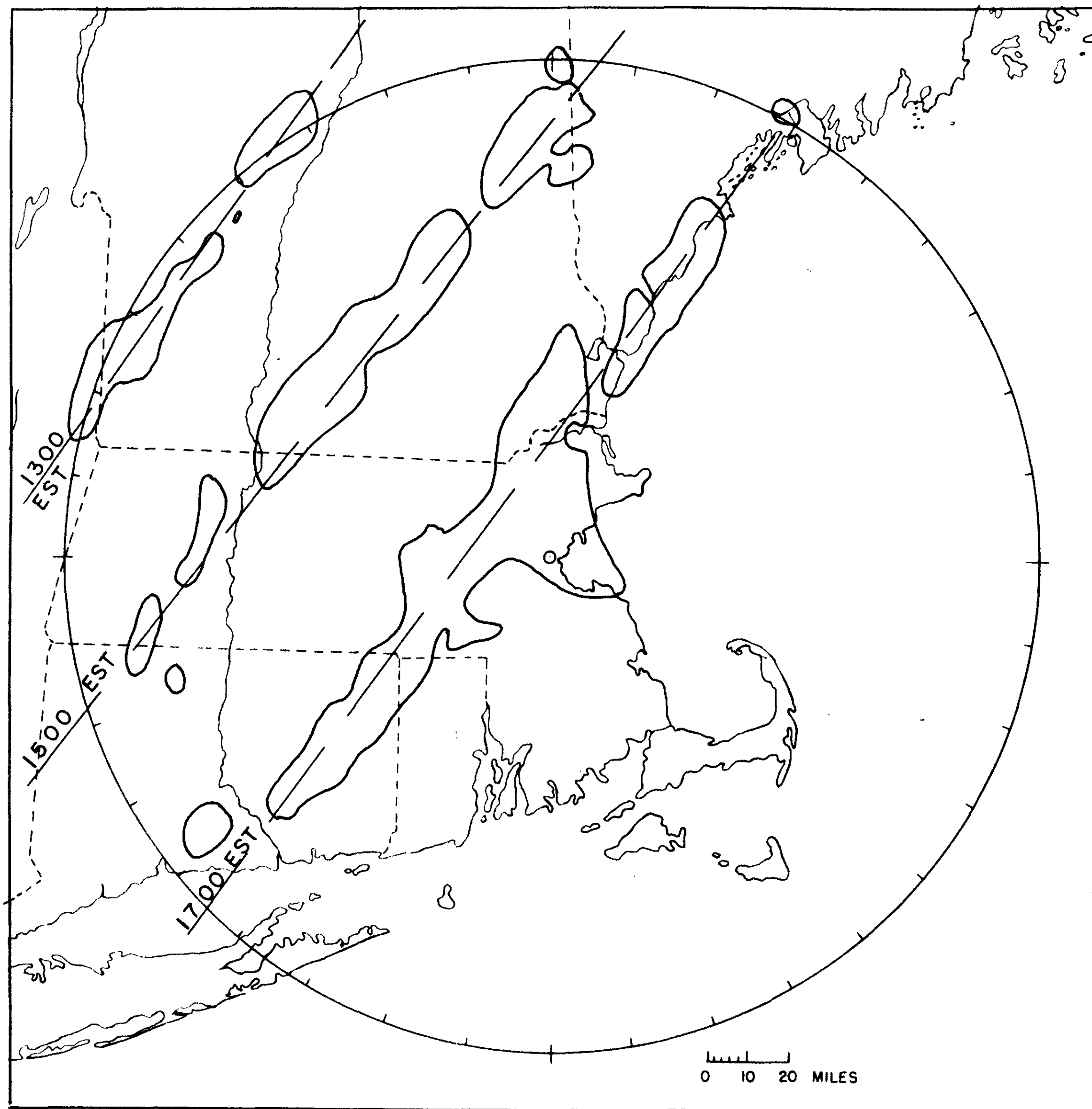


Fig. 7b General progression of the squall line as shown by the radar.

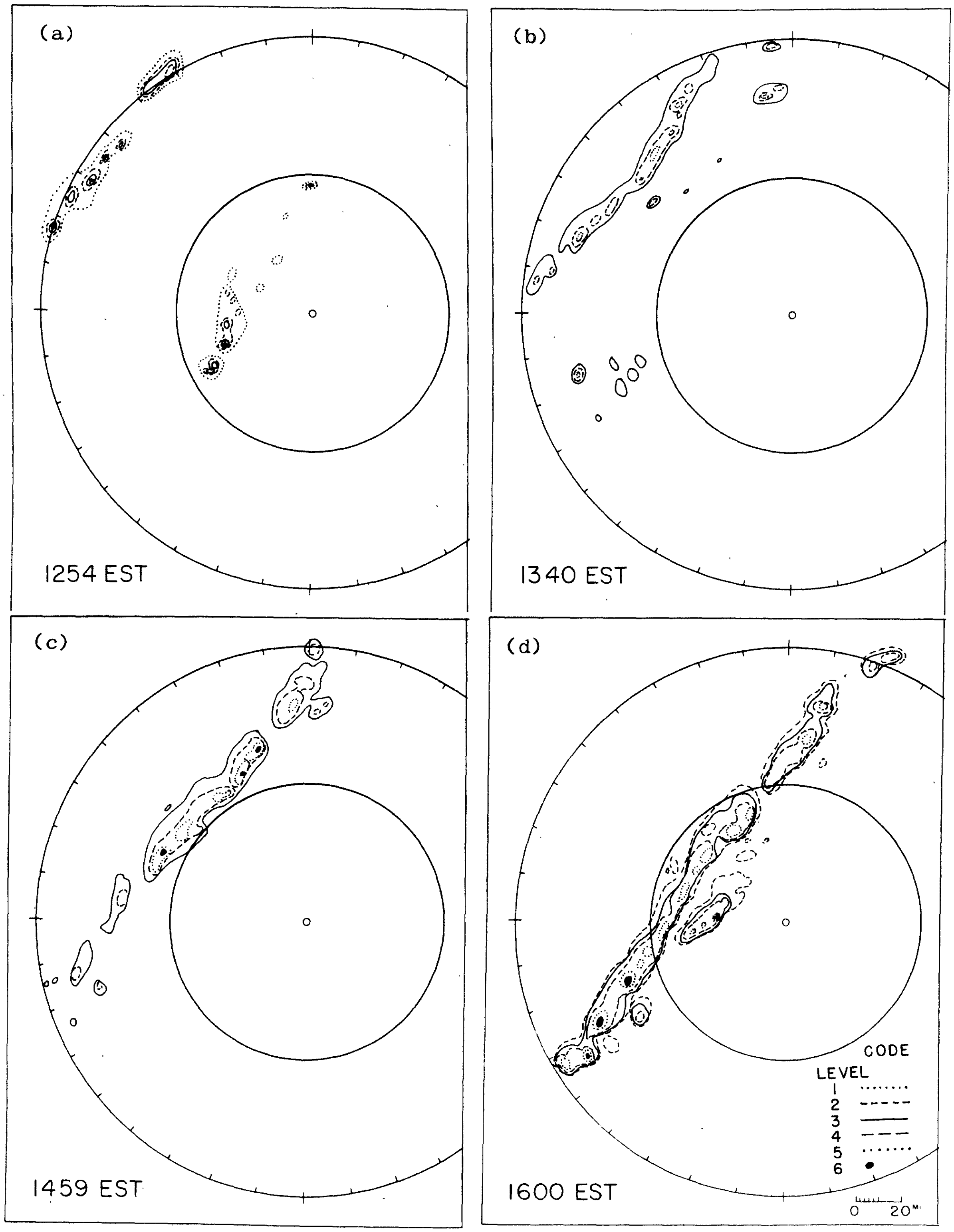


Fig. 8 PPI maps showing the general storm development within the squall line.

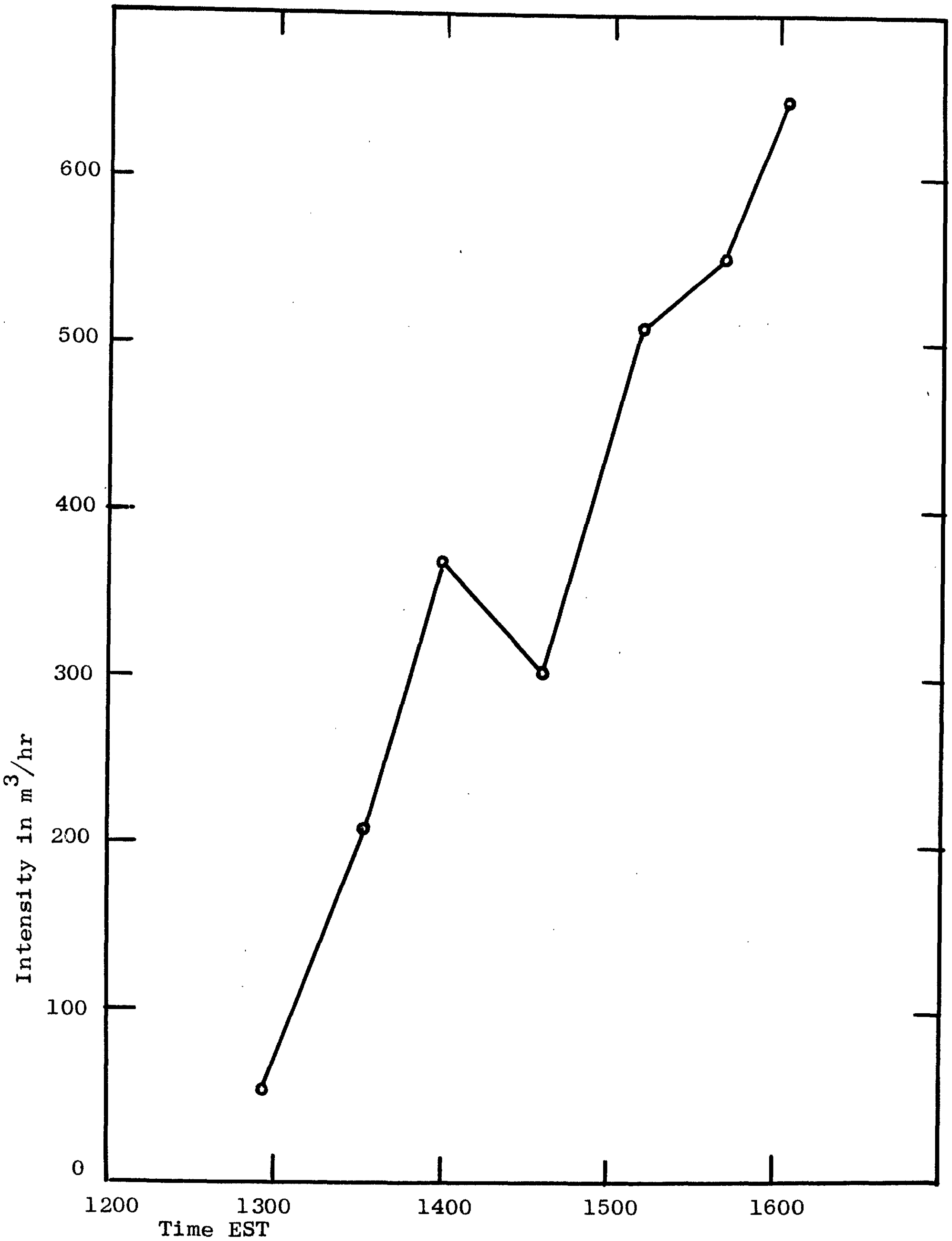


Fig. 9 Variation of total rainfall intensity of the squall line.

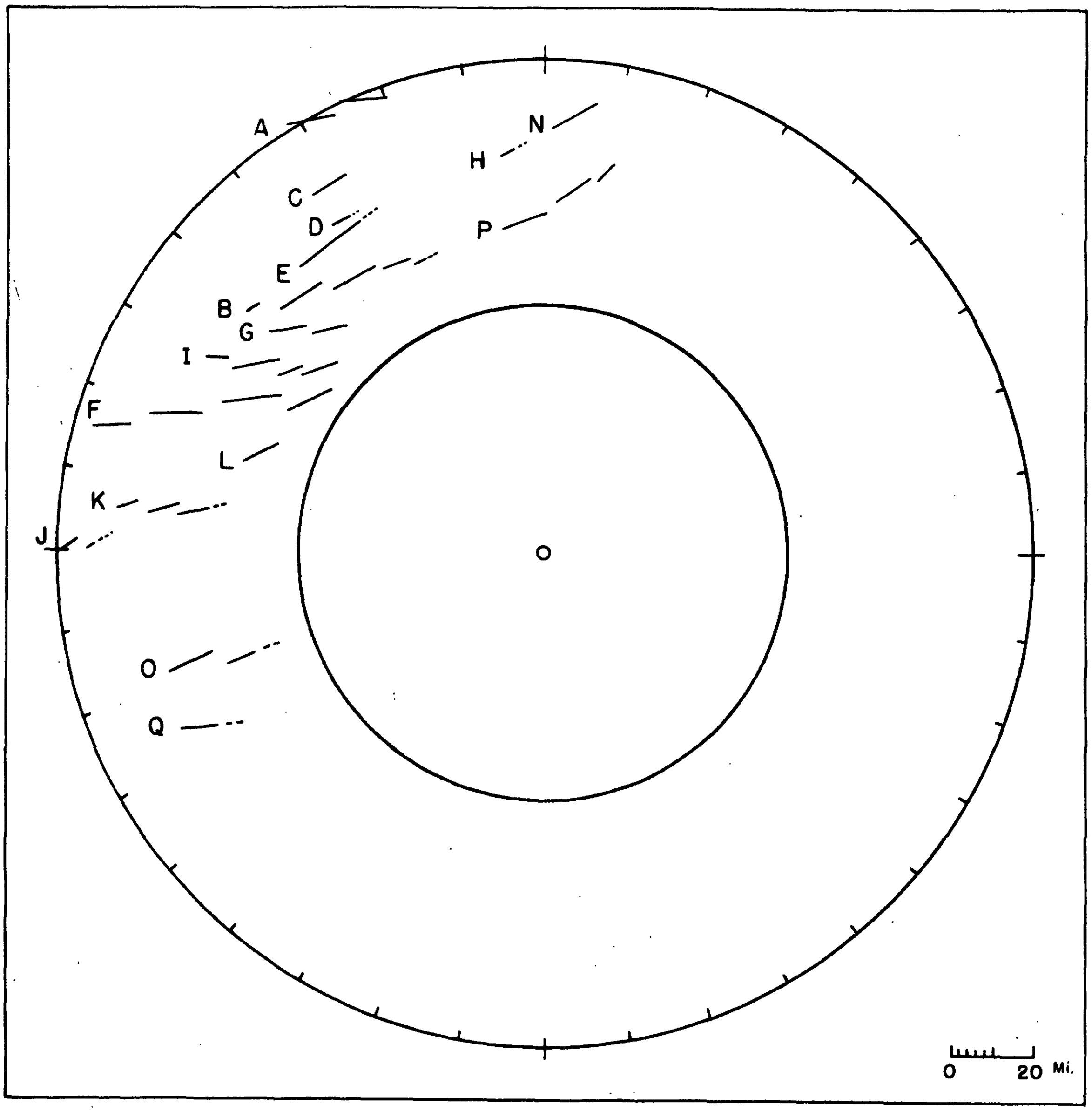


Fig. 10 Tracks of the intense cells within the squall line. Dashed lines indicate when cell motion can no longer be followed.

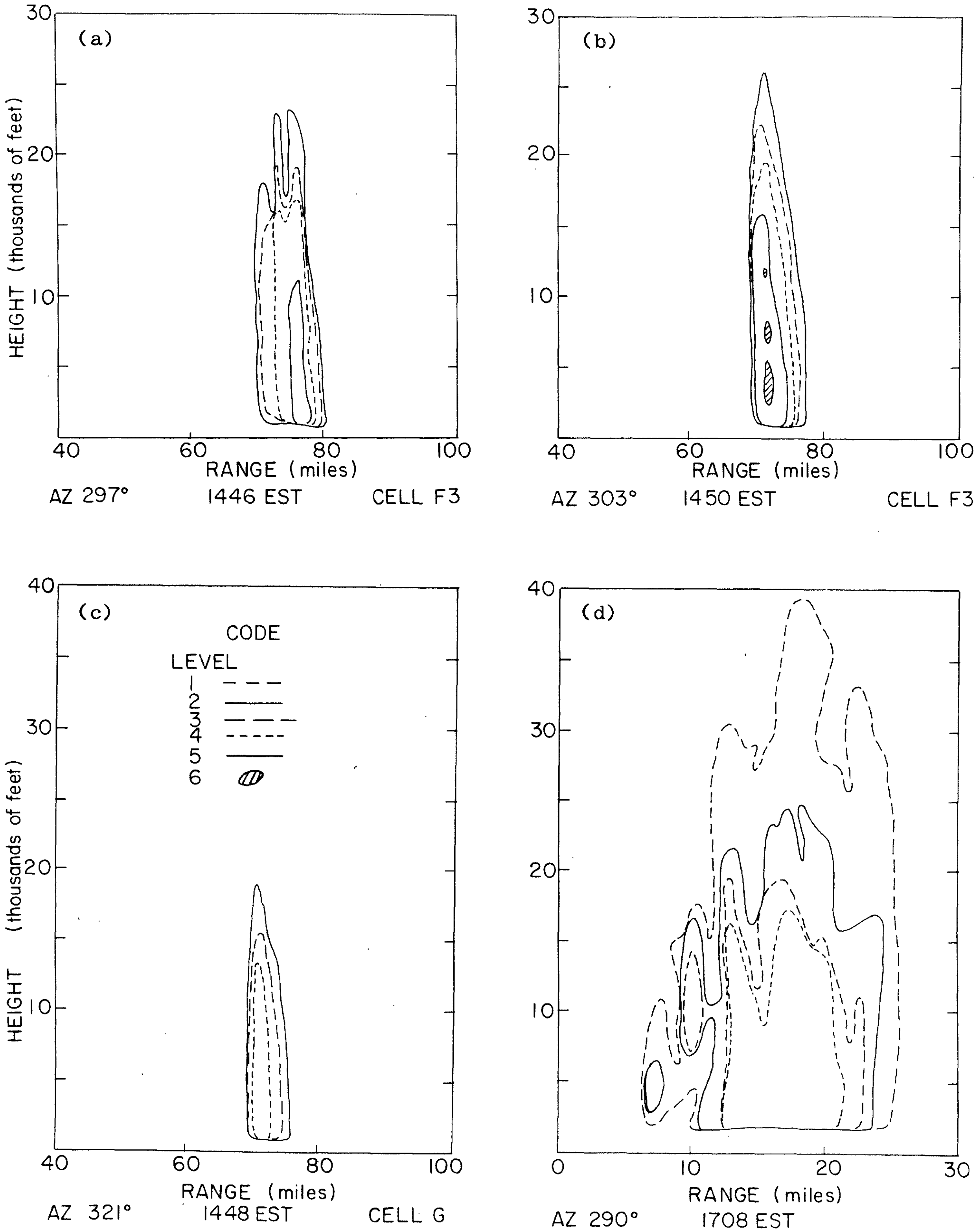


Fig. 11 RHI display of vertical sections through portions of the squall line.

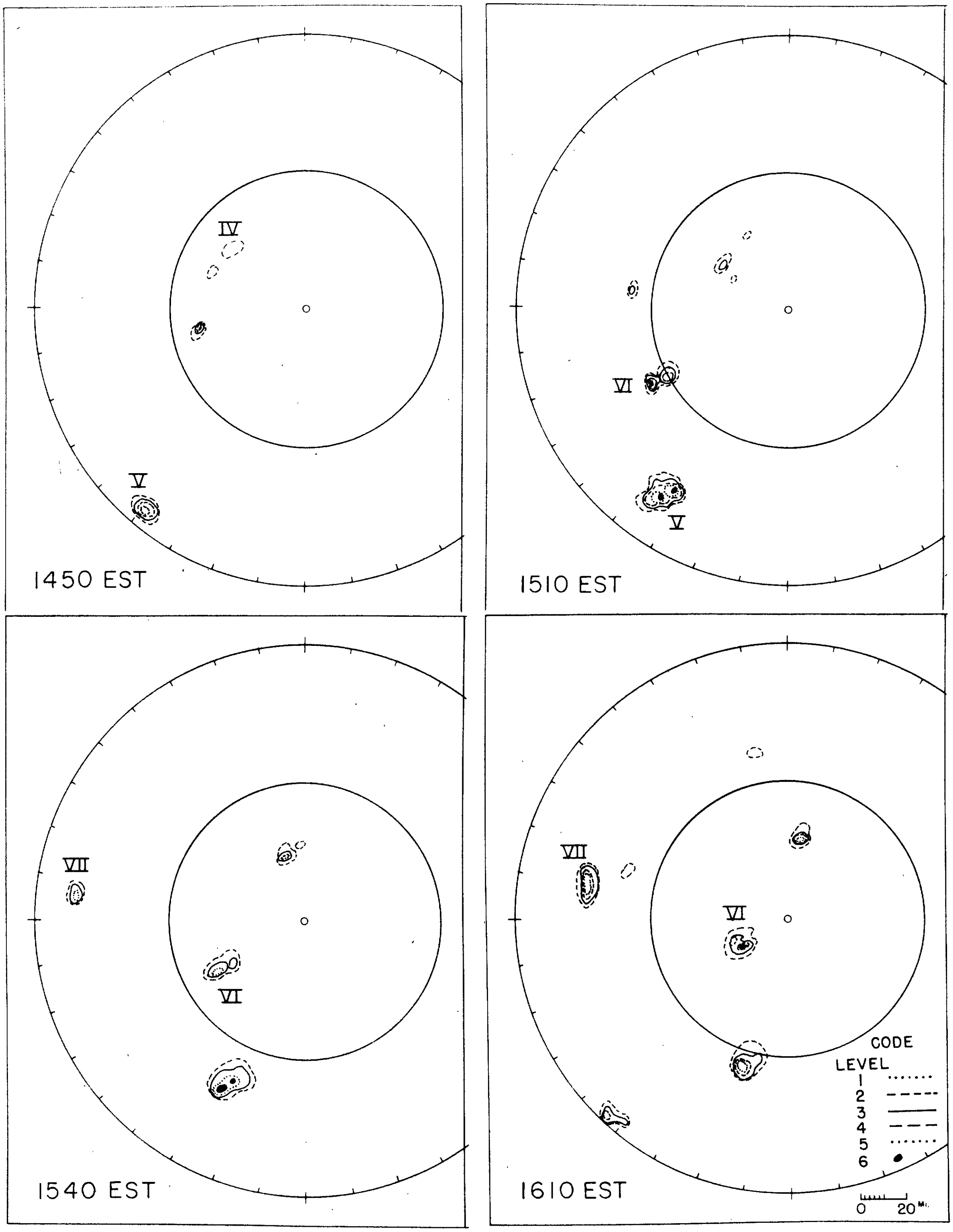


Fig. 12 PPI maps showing the location of some of the air mass storms of August 28, 1965.

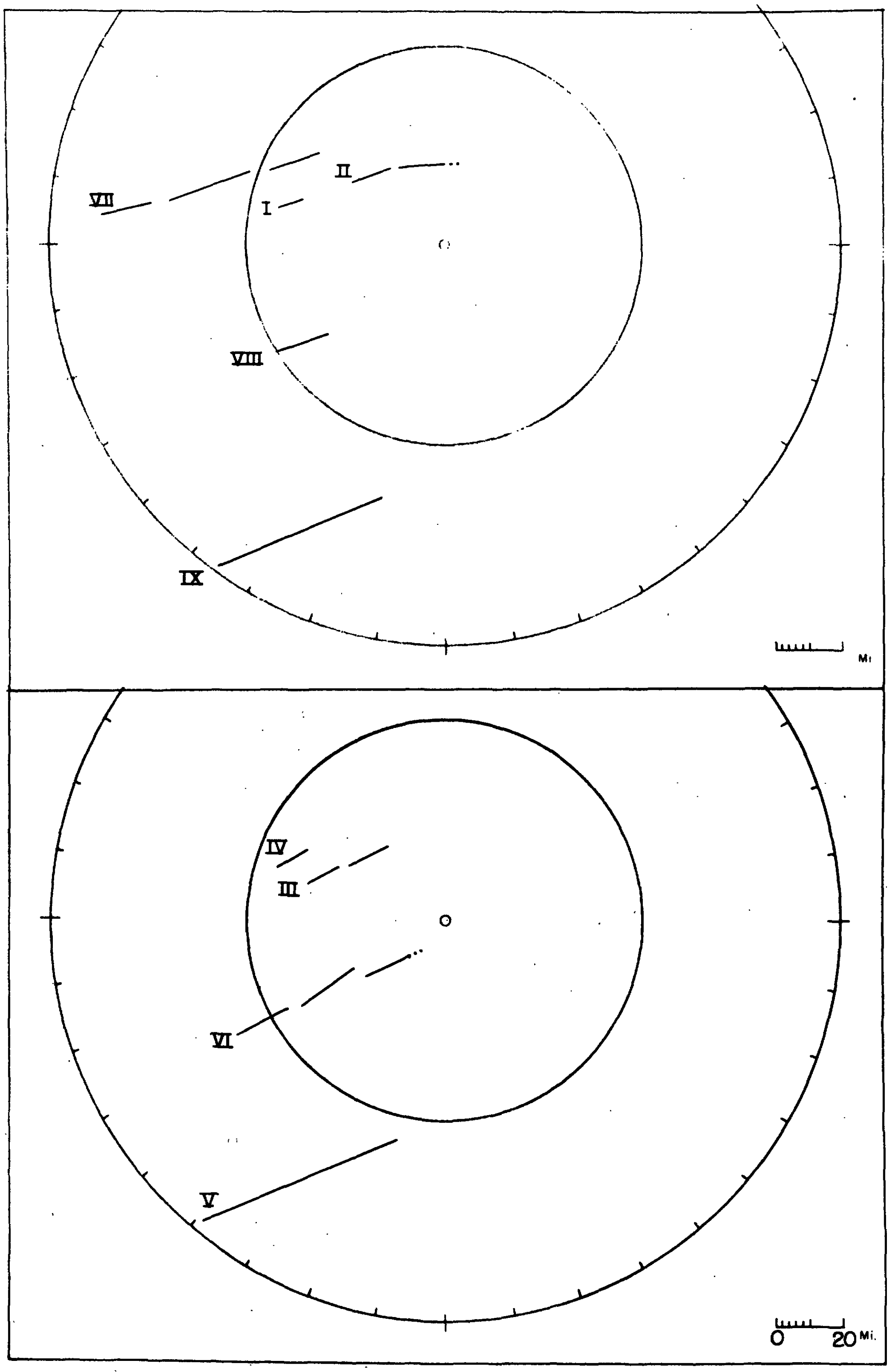


Fig. 13 Tracks of the air mass thunderstorms. Dashed lines indicate when storm motion can no longer be followed.

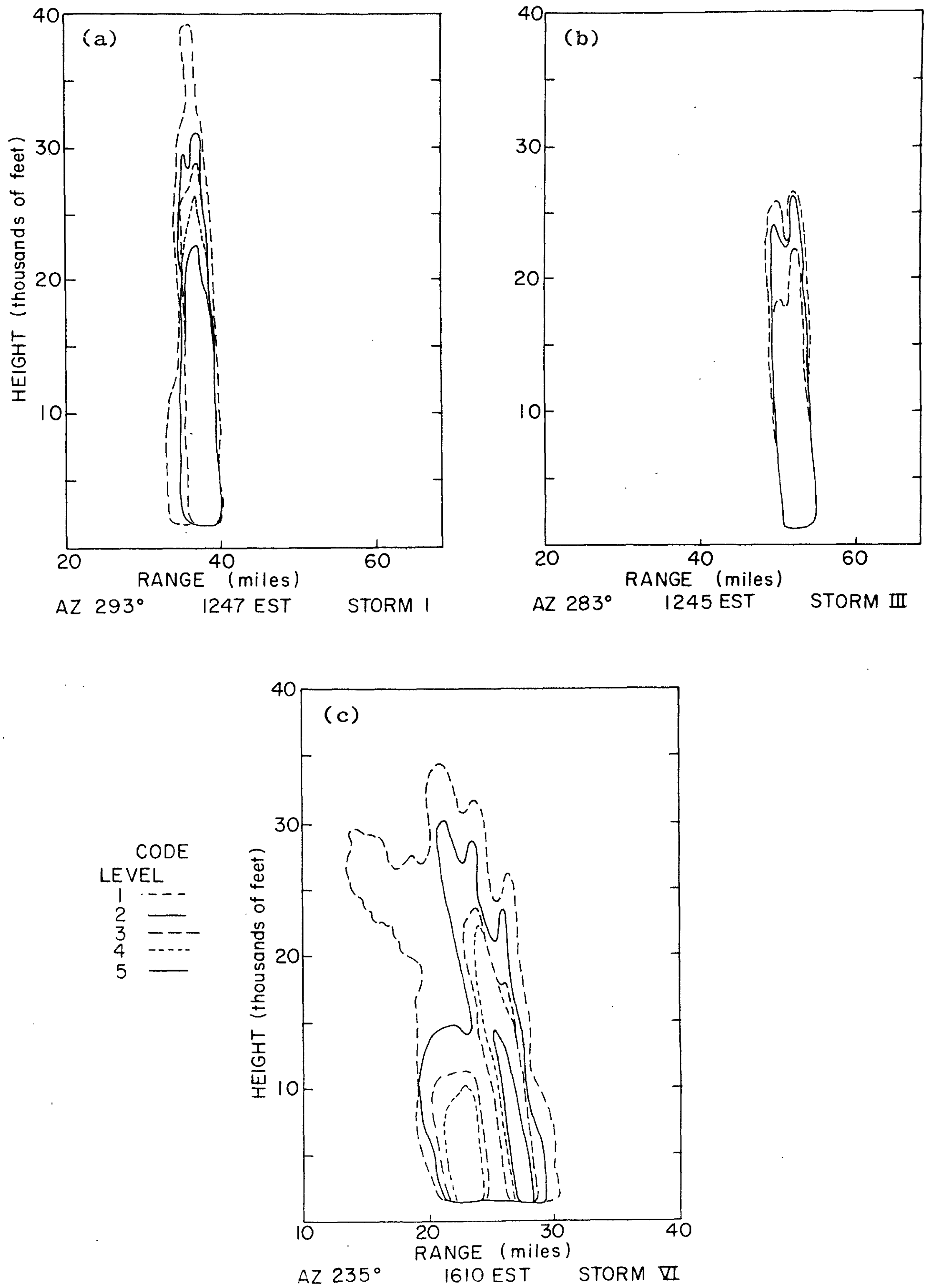


Fig. 14 RHI display of vertical sections through Storms I, III and VI.

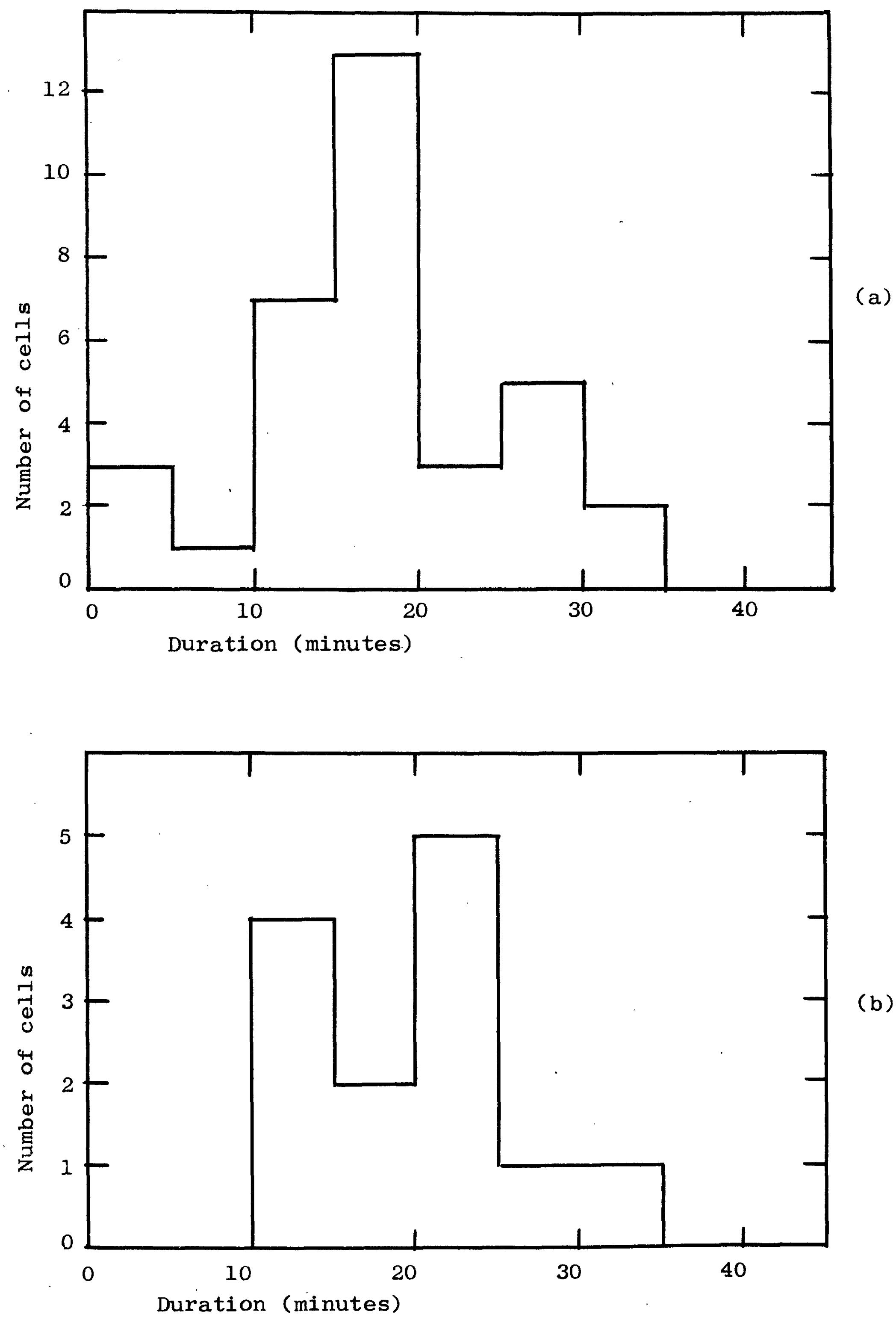


Fig. 15 Histograms of cell duration. (a) squall line; (b) air mass storms.

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